"Technology impulses nations"

(Technical University of Madrid's motto)

UNIVERSITY OF PISA

Faculty of Engineering

Master’s Degree in
Hydraulics, Transport and Regional Territory Engineering

CHARACTERIZATION OF PAVEMENT BEARING CAPACITY BY TRAFFIC SPEED DEFLECTOMETER

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ABSTRACT

Traffic Speed Deflectometer is a high-efficiency tool to determine the bearing capacity at network level. Denmark, UK, Italy, Poland, South Africa, Usa and China are the States that are equipped with this device and are conducting extensive research on it.

The purpose of this work is to give a contribution in confirming the reliability of the TSD against the traditionally instruments. This has been achieved by: assessing the influence of surface irregularities on the measurement by Traffic Speed Deflectometer and correcting the measurement of bearing capacity according to the temperature of the pavement.

RIASSUNTO ANALITICO

Il Traffic Speed Deflectometer è uno strumento ad alto rendimento nella misura della capacità portante delle pavimentazioni a livello di rete. Danimarca, Inghilterra, Italia, Polonia, Sudafrica, Usa e Cina sono gli Stati che si sono dotati di questo dispositivo, sul quale stanno conducendo ricerche approfondite.

Lo scopo di questo lavoro sarà quello di dare un contributo nel confermare l'affidabilità del TSD nei confronti degli strumenti tradizionalmente utilizzati. Questo è stato ottenuto: valutando l'influenza delle irregolarità superficiali sulla misura con Traffic Speed Deflectometer e apportando delle correzioni alla misura di portanza in funzione della temperatura della pavimentazione.

CONTENTS

INTRODUCTION

The bearing capacity of a pavement is one of the basic parameters to establish a program of maintenance on the existing infrastructure and also for the acceptance of renovation works or of new constructions. The devices use up to now allow to determine the structural characteristics of the layers of the pavement in accordance with discrete measurements which require the stationing of the instrument for a few minutes on the test station or allow, in other case, the measurement while moving, but at low speeds. This requires a certain amount of time even for a limited road section, in addition to the necessity of a traffic diversion which cause traffic disruption and danger to the safety of workers.

In 2000, Greenwood Engineering developed the prototype of Traffic Speed Deflectometer able to overcome the limitations of traditional instruments, relatively to the discretization of the measures, resulting in the continuous deflection bowl of the pavement at speeds comparable to traffic speed. In 2010 it was delivered to ANAS S.p.A (the third specimen existing) to use it in its road network (total size equal to 31000 km) to manage a maintenance program or for the acceptance of new work. The potential of this device would allow, in theory, an investigation of the entire ANAS's network in less than two months, with measures spaced 2 cm.

This high-performance tool, as all the news, reported an initial detachment or in other case a real opposition from various parties involved in the construction of roads. The purpose of this thesis is to contribute on the evaluation of the TSD reliability compared to traditional measurement devices of bearing capacity because this tool is in the new ANAS performance specifications for operation control and acceptance.

The research began with an analysis of the studies on TSD in the technical literature with particular attention to those produced by the National Agencies in possession of this tool. It has appeared that the problem of the influence of temperature on the measure is treated differently in the individual States and none have never conducted specific studies on the influence of surface irregularities of the pavement on the determination of the bearing capacity by Traffic Speed Deflectometer.

Thanks to the surveys by TSD and FWD provided by ANAS S.p.A, it was possible to study the influence of these two factors. Due to the amount of data, it was necessary to create a program in PHP that could manage the results of the surveys, fix appropriate constraints and selection criteria to determine the reliability of the TSD in its use at network level.

The results of the study confirm the reliability of the equipment and quantify the effects on the bearing capacity measurements of temperature and pavement irregularities along the section of investigation.

INTRODUZIONE

La capacità portante di una pavimentazione è uno dei parametri fondamentali sia per stabilire un programma di interventi manutentivi su infrastrutture esistenti che per l'accettazione dei lavori di ripristino e di nuova realizzazione.

Gli strumenti fino ad ora impiegati consentono di determinare le caratteristiche strutturali degli strati della pavimentazione secondo misure puntuali che necessitano lo stazionamento dello strumento per alcuni minuti sulla postazione di prova oppure consento la misurazione in movimento, ma a velocità molto ridotta. Tutto ciò richiede un certo tempo anche per una limitata sezione stradale, oltre alla necessità di una deviazione del traffico veicolare portando con sé disagi alla circolazione e pericolo per la sicurezza degli operatori impiegati.

Nel 2000 viene sviluppato dalla Greenwood Engineering il prototipo di Traffic Speed Deflectometer in grado di superare i limiti delle tradizionali strumentazioni, relativamente alla discretizzazione delle misure, determinando in continuo il bacino di deflessione della pavimentazione a velocità comparabile a quella del traffico veicolare circostante. Nel 2010 viene consegnato il terzo esemplare esistente ad ANAS S.p.A per un suo utilizzo nella rete stradale di sua competenza (estensione complessiva pari a 31000 km), sia per gestire un programma di manutenzione che per l'accettazione di nuove lavorazioni. La potenzialità di tale strumento permetterebbe, in via teorica, un'indagine dell'intera rete ANAS in meno di due mesi, potendo disporre di misure distanziate di 2 cm. Questo strumento ad alto rendimento come tutte le novità ha registrato un'iniziale freddezza, se non una vera opposizione da parte dei diversi soggetti coinvolti nella costruzione di pavimentazioni stradali. Lo scopo del presente lavoro di tesi è quello di contribuire alla valutazione dell'affidabilità del TSD rispetto agli strumenti di misura della portanza tradizionali, in quanto tale strumento è previsto per le operazione di controllo e accettazione nel nuovo capitolato prestazionale ANAS.

Il lavoro di ricerca è iniziato con l’analisi degli studi sul TSD presenti nella letteratura tecnica con particolare attenzione a quelli prodotti dalle Agenzie Nazionali in possesso di tale strumento. È emerso come il problema dell’influenza della temperatura sulla misura venga trattato in modo tanto diverso nei singoli Stati, mentre non sono mai stati condotti studi specifici sull’influenza delle irregolarità superficiali della pavimentazione sulla determinazione della capacità portante mediante Traffic Speed Deflectometer.

Grazie ai rilievi TSD e FWD messi a disposizione da ANAS S.p.A, è stato possibile studiare l’influenza di questi due fattori. A causa della notevole mole di dati, si è reso necessario creare un programma in linguaggio PHP, in grado di gestire i risultati dei rilievi, fissare opportuni vincoli di selezione e determinare i criteri di affidabilità delle misure TSD nel suo utilizzo a livello di rete.

I risultati dello studio, nel confermare l’affidabilità dell’apparecchiatura, hanno permesso di quantificare gli effetti della temperatura della pavimentazione e delle irregolarità presenti lungo il tratto di indagine, sui rilievi di portanza.

Chapter 1

PAVEMENT BEARING CAPACITY AND MEASUREMENT DEVICES

1.1 Pavement bearing capacity

Pavement bearing capacity is an important design property which defines the ability of the pavement structure to withstand traffic loads at various environmental conditions. It is an important component of Pavement Management System (PMS) to quickly identify sections that may be structurally-deficient so providing vital information about the current and future conditions of these pavements, can assist National Agencies in selecting suitable maintenance and rehabilitation strategies and appropriately allocate available funds.

A test to directly measure pavement strength or structural capacity does not exist. At the beginning coring, excavation, and sampling techniques were traditionally used but these methods were destructive, had significant impact on traffic and high cost in terms of time and expenditure spent to restore the condition of the tested pavements. Therefore to overcome these shortcomings Non-Destructive Testing (NDT) represented a very effective approach to assess the structural capacity of existing pavements. Numerous NDT methods have been introduced and modified for more efficient testing over the last several decades and they plays an important role in pavement management. These methods can generally be categorized as either seismic-based or deflection-based methods. Seismic-based methods measure the velocities at which low-strain stress waves propagate through the pavement. Deflection-based methods involve applying a large force to the pavement and measuring the induced deflections. Both methods are used to determine the elastic properties which are then used to predict the pavement capacity and remaining life.

All seismic-based and deflection-based nondestructive methods are performed at discrete points and these results are then used to characterize the entire pavement. The more tests performed, the better the predictions, though there is never complete assurance that all critical locations have been tested. Another weakness of discrete measurements is that it is difficult to separate the effects of the elastic properties of the pavement from the pavement geometry. For example, larger deflections will be measured near a joint or free edge. However, in discrete tests it is difficult to differentiate increased deflections created by joints and edges from increased deflections created by a softer pavement.

Pavement deflection testing is currently the most widely used and deflection data analysis provides qualitative and quantitative assessment of the structural integrity and bearing capacity of all layers of the pavement, as well as the condition of the subgrade and remaining service life. Approaches and the equipments that have been developed for pavement deflection testing are briefly discussed in the next paragraph, and a perspective is offered on how these different methods of pavement testing compare.

1.2 Static and pseudostatic deflection measurements

A number of static or pseudostatic deflection testing methods have been developed. Static tests use a stationary, nontime-variant force to induce the measured displacement. Pseudostatic measurements use time-variant loadings that approximate a static loading. Typically, pseudostatic loads for deflection testing are slowly moving wheel loads.

1.2.1 The Benkelman Beam

Figure 1 - 1 The Benkelman beam

In 1953, A. C. Benkelman of the U.S. Bureau of Public Roads developed this device that bears his name. The Benkelman beam was first used on the 1953 WASHO Road Test and it is a simple device used to measure pavement deflections induced by a stationary truck wheel. A simplified drawing of side and plan views of the Benkelman beam is shown in figure 1-2.

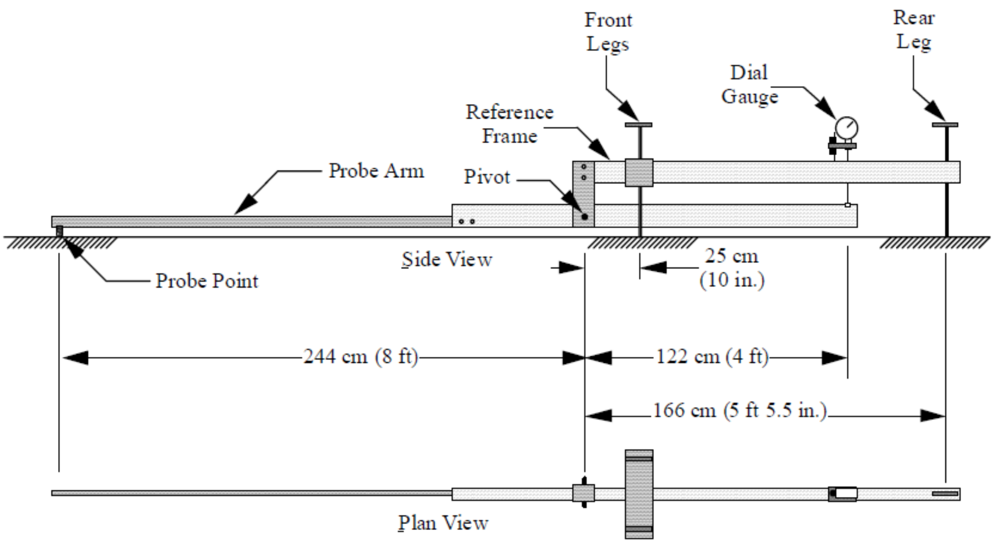


Figure 1 - 2 Simplified drawing of Benkelman beam

The Benkelman beam consists of a reference frame supported by three legs. A probe arm pivots at the reference frame. The probe arm extends forward from the pivot 244 cm to a probe point, which rests on the pavement at the point where deflections are to be measured. The probe arm also extends 122 cm behind the pivot, where a dial gauge measures the relative vertical distance between the pivot arm and the reference frame. Benkelman beam testing is usually performed during the unloading of the pavement. To perform the tests, a truck with dual rear wheels and a known wheel load is positioned on the pavement with one set of dual wheels at the measurement point. The Benkelman beam probe point is then positioned between the dual wheels. The reference frame is next leveled, and an initial dial gauge reading is made. The truck is moved forward more than 244 cm and a second dial gauge reading is made. The pavement rebound is equal to twice the difference between the final and initial dial gauge readings. Testing can also be performed by making an initial dial gauge reading with the pavement unloaded, and then loading the pavement for a final reading. Additional measurements can be made with the load at various locations relative to the probe. To obtain accurate results with the Benkelman beam, the deflected region of a pavement must be limited to a radius of less than 244 cm around the loading point. Otherwise, the reference frame portion of the Benkelman beam will not remain fixed during the course of the test, resulting in a measurement that under-represents the total deflection. Thick rigid pavements are very likely to have deflected regions larger than what the Benkelman beam is capable of measuring. In these cases, one or two additional Benkelman beams can be used. The additional devices are used to measure the deflections at the front legs, and perhaps the rear leg, of the primary Benkelman beam.

The equipment required for Benkelman beam testing is simple and inexpensive. Testing can be easily performed by a crew of three technicians. Typical daily production for such a crew is 50-100 test points per day.

1.2.2 The Traveling Deflectometer

Figure 1 - 3 The Traveling Deflectometer

Between 1955 and 1960, the California Division of Highways developed a device based on the Benkelman beam called the traveling deflectometer. This one-of-a-kind device was a truck-trailer unit having dual probes to simultaneously measure the deflection between each set of dual wheels. With this device, deflection measurements were performed at 3.8 m intervals while traveling at a steady rate of 0.8 km/h. A total production of 1500-2000 test points per day by a crew of one technician has been reported. The fact that it was not more widely produced may indicate that it did not live up to its expectations or initial performance.

1.2.3 The CEBTP Curviameter

Figure 1 - 4 The CEBTP Curviameter

Another device that operates on principles similar to those of the Benkelman beam is the Centre Experimental de Recherches et d'Ettudes du Batiment et des Travaux Public (CEBTP) Curviameter (1978). This French vehicle measures not only pavement deflections, but also the radius of curvature of the pavement deflection bowl. Testing is performed at discrete points every 11.45 m as the vehicle moves at a constant speed of 18 km/h. The CEBTP Curviameter has a continuous chain that moves at the same velocity as the vehicle. The chain is positioned on the ground about 2.5 m in front of a pair of dual rear wheels of the truck. The chain passes back between the dual wheels and behind the wheels for more than 1.5 m, and then back up over the rear wheel. As the truck moves forward, it constantly places the chain down in front of the rear wheels. The chain remains at a fixed location on the pavement as the truck wheels roll over it. One or more geophones are attached to this chain. Testing proceeds in the following manner. When the geophone arrives at a position on the ground 2 m in front of the rear axle, a recording device begins to record the output from the geophone. The geophone remains at the same position on the pavement as the dual rear wheels roll over it, deforming the pavement. The measurement continues until the geophone is 1 m behind the rear axle. The vehicle continues forward until the geophone (or another geophone) is again in position for another test. The geophone makes a measurement of vertical particle velocity at the pavement surface. The pavement deflection is calculated by simply integrating the geophone output. The production rates and testing interval are dependent upon the number of geophones on the continuous chain. With one geophone on the chain, the testing interval would be about 5 m and the daily production would be about 2500 test locations per day.

1.3 Dynamic deflection testing

Another class of deflection testing methods uses a dynamic force to generate pavement deflections. There are two different types of dynamic forces that can be applied to the pavement. The first is a steady-state sinusoidal excitation. With this monochromatic type of excitation, all of the dynamic force is at a single frequency. The second type of dynamic force is a broadband excitation, where the force energy is distributed over a range of frequencies. A broadband force can be obtained in a number of ways, but the means employed in pavement deflection testing is an impulsive force generated with a drop weight.

1.3.1The Dynaflect

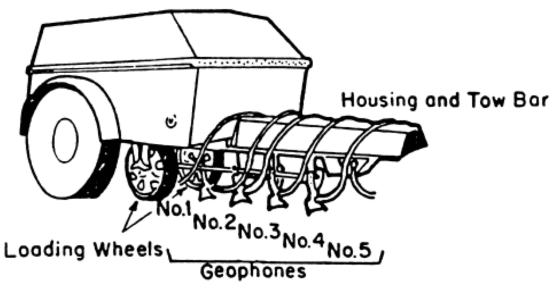


Figure 1 - 5 The Dynaflect

The first dynamic displacement measurement technique was the Dynaflect. It was first developed in 1964 by the Lane-Wells Company. The Dynaflect is a trailer-mounted device that uses two eccentric rotating masses to generate a monochromatic vertical force. This dynamic force is applied to the pavement through two steel wheels. The force is applied at a fixed frequency of 8 Hz with a force level of 4.45 kN peak. The trailer has a dead weight of 7.12 kN, which supplies the hold-down force required to keep the loading wheels in contact with the ground. The displacements induced by this force are measured with five geophones. A plan view of the typical arrangement of the loading wheels and the geophones for Dynaflect testing is shown in figure 1-6.

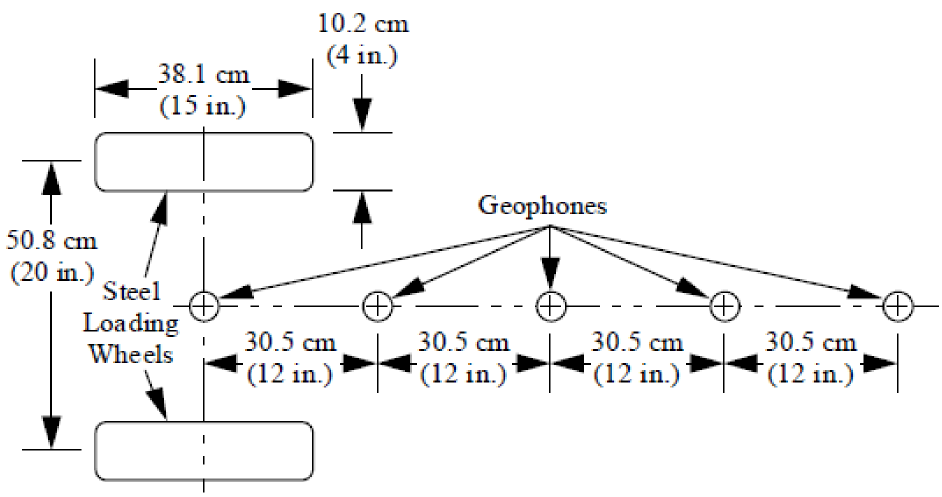


Figure 1 - 6 Plan view of typical loading wheel/geophone arrangement for Dynaflect

One geophone is positioned at the midpoint between the loading wheels, and the other four geophones extend out in a linear array to measure the deflection basin. No measurement of pavement deflection is made at the points of load application. The testing is conducted by positioning the device at the testing location. A motorized lift system then lowers the steel loading wheels and, in the process, raises the trailer’s pneumatic wheels off the pavement. The geophones are then lowered into contact with the pavement. A motor begins spinning the eccentric masses. The rate of rotation of the spinning masses is monitored. When the spinning rate has come to equilibrium at 8 Hz, the output from each geophone is recorded. Deflections are determined from these outputs. If the next test location is a short distance away, the geophones are raised off the pavement and the Dynaflect is rolled to the next location on the steel loading wheels at speeds less than 16 km/h. If higher towing speeds are required, then the steel loading wheels are raised and the trailer is pulled on the pneumatic wheels. The Dynaflect has been used fairly widely around the world. A typical production rate for a crew of two technicians is 100-400 test locations per day.

1.3.2 The Road Rater

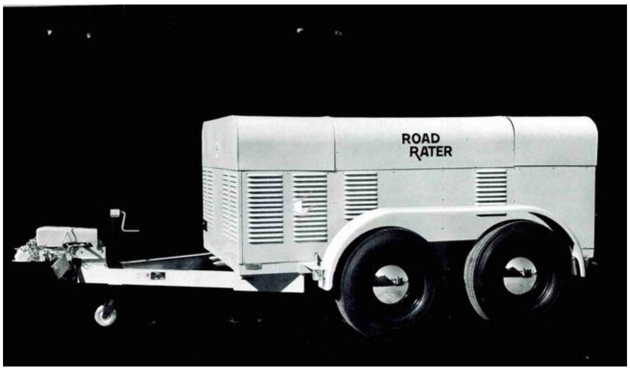


Figure 1 - 7 The Road Rater

The Road Rater is a device functionally similar to the Dynaflect. Both devices are trailer-mounted. They both apply dynamic forces to the pavement, and they measure the induced deflections with an array of geophones. The Road Rater uses a hydraulic system to accelerate a reaction mass up and down, generating the vertical dynamic force. Unlike the Dynaflect, the frequency and magnitude of the dynamic force can be varied on the Road Rater. Various sizes of Road Raters have been built. The smallest can generate peak dynamic force levels of 2.22 kN-8.9 kN. The largest device can generate peak dynamic forces from 4.45 kN to 35.6 kN. The hold-down force is supplied by the weight of the trailer. Loading frequencies from 5 to 70 Hz can be used The force is applied to the pavement through a rectangular or circular steel plate. Plates of various sizes and shapes have been used with the Road Rater. All plates have a hole in the center, through which a deflection measurement is made. The applied vertical force magnitude is measured with a load cell. The Road Rater uses a linear array of four or five geophones extending away from the loading plate. One geophone is positioned at the center of the plate, and a spacing of 30.5 cm between geophones is typically used. Testing can be performed at various force and frequency levels with the Road Rater. This testing can be used to study nonlinear behavior and frequency effects of pavement systems. Typical production for the Road Rater operated by a crew of one or two technicians is 100-400 test locations per day.

1.3.3 Rolling Daynamic Deflectometer

The RDD was constructed by modifying a Vibroseis which is used in exploration geophysics to apply large dynamic forces to the ground in order to generate seismic waves for oil prospecting. The RDD requires similar dynamic forces. Thus, the Vibroseis was an ideal beginning point in the development of the RDD. Photographs of the Vibroseis truck and the RDD are shown in figures 1-8 and 1-9.

Figure 1 - 8 The Vibroseis truck

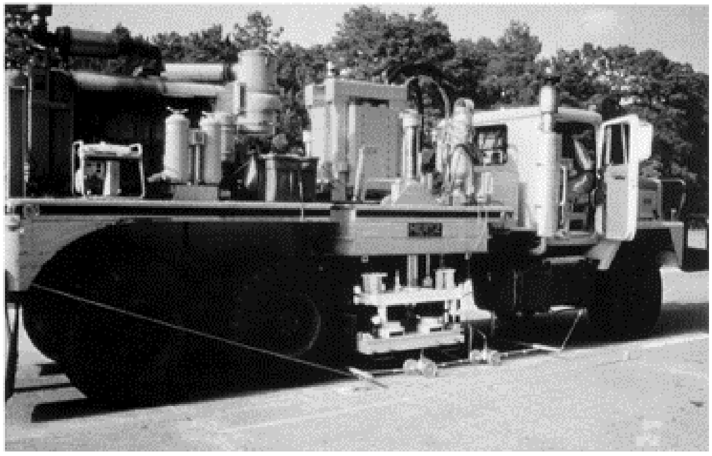


Figure 1 - 9 The Rolling Daynamic Deflectometer

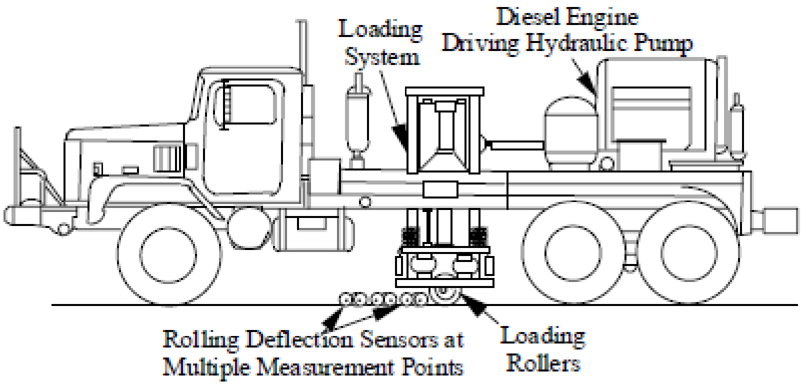


Figure 1 - 10 Drawing of the RDD

A line drawing of the RDD that identifies important components is shown in figure 1-10. The truck has a gross weight of about 195 kN. A large diesel engine on the rear of the truck powers a hydraulic pump. This hydraulic system powers the loading system, which applies a combined static and dynamic force to the pavement through two loading rollers. The displacements induced by the applied dynamic force are sensed with multiple rolling sensors that are pulled along with the truck.

Dynamic forces are generated by cycling hydraulic fluid in and out of the top and bottom chambers of the hydraulic actuator inside the reaction mass. The hydraulic pressure in the actuator accelerates the 33.4 kN reaction mass up and down. This system is capable of generating dynamic forces up to 154 kN peak at frequencies from 5 to 100 Hz. The dynamic forces are transferred down the stilt structure, to the loading frame, and then through the loading rollers to the pavement. The force applied to the pavement is measured with load cells located between the loading frame and the bearings of the loading rollers.

The dynamic loading system is capable of generating forces much greater than the dead weight of the loading system. This could cause the entire loading system to momentarily lift off the pavement and then slam back down to the pavement. To prevent the loading rollers from lifting off the pavement, a static loading system is also provided. The static loading system is comprised of two hydraulic cylinders, one on either side of the truck. These cylinders apply a static force to the loading system through two pairs of air springs. The air springs provide for compliance in the static loading system and act as isolators, reducing the vibrations in the truck caused by the dynamic forces.

The sensors can be positioned in any number of locations relative to the loading rollers, and they are pulled along with the truck by a vibration-isolated towing system. The locations of the rolling sensors are selected to meet the requirements of the particular study. The most important sensor location is the midpoint between the two loading rollers.

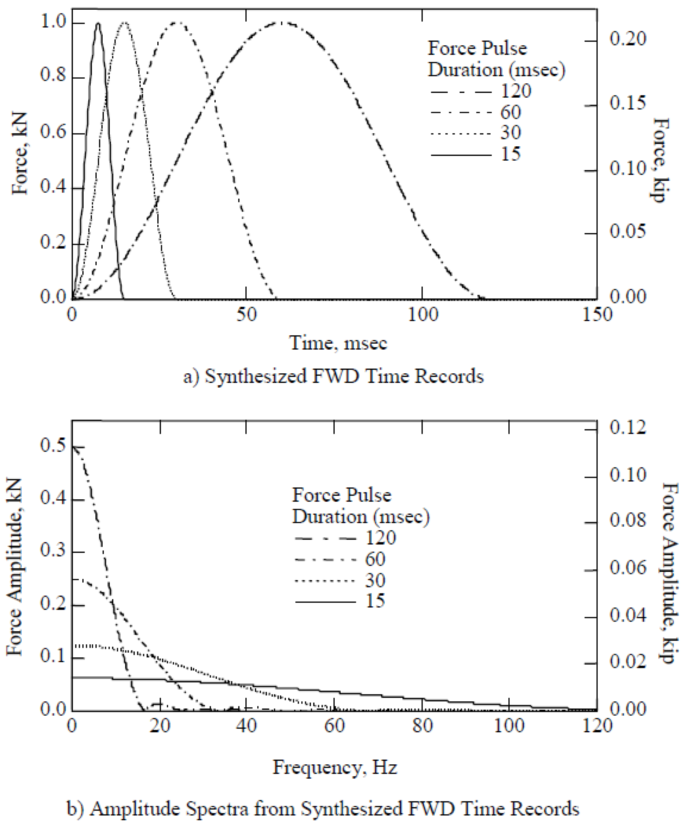
The outputs from the load cells, the loading rollers, and a distance-measuring device, which tracks the RDD position, are recorded on a PC-based data acquisition system. This data acquisition system incorporates filters and amplifiers to provide for high-quality measurements.
In general, RDD testing is performed at speeds of 0.3-0.6 m/s so if a testing velocity of 0.6 m/s is used, and the filter averages results over 2 second time intervals, the spatial measurement resolution of the measurement is 1.2 m. Slower testing speeds are used for high-resolution testing.

The operating frequency is selected based on the site subgrade conditions, the pavement roughness and operating velocity, and on sensor contact considerations. Generally, the operating frequency is between 20 and 80 Hz. Force levels are selected based primarily on the estimated strength of the pavement to be tested. The possible range in dynamic forces is 13-300 kN peak-to-peak. A static force level is selected that will keep the loading rollers in contact with the pavement.

1.3.4 The Falling Weight Deflectometer

Figure 1 - 11 The Falling Weight Defelctometer of University of Pisa

The FWD is a best-known pavement surface deflection measurement device used for structural analysis and was first developed in Europe in 1972. The FWD is a trailer-mounted device used to apply an impulsive dynamic force to the pavement and measure the induced deflections. Three different FWDs have been developed: the Dynatest FWD, the Phoenix FWD, and the KUAB FWD. The Dynatest is the FWD device most commonly used within around the world. All three devices apply a broadband impulsive force to the pavement by dropping a weight on a spring-loaded pad and recording inertially referenced deflection measurements of the induced deflections. The FWD was designed to apply a force pulse to the pavement in an action similar to the loading applied by moving vehicular traffic. Research with transducers buried in pavement indicates that the wheel loads of a truck traveling 80 km/h will load the pavement with a force pulse about 120 msec wide. The force level and duration of FWD loading can be varied by changing the mass of the drop weight, the drop height, and the stiffness of the pad that the drop weight strikes. The stiffness of the pavement also influences the level and duration of FWD force pulses. Force levels of 4.45 kN-156 kN in figure and force pulse durations of 30 msec-40 msec can be achieved with various FWD devices. The frequency content of an FWD impulse is determined by the shape and duration of the force pulse. For example, synthesized FWD time records with durations of 120, 60, 30 and 15 msec are shown in figure 1-12a. These force pulses are haversine shaped, which is a good approximation for the shape of traffic or FWD force pulses. All of the force pulses have a peak value of 1 kN. Frequency spectra for the four force pulses are shown in figure 1-12b.



a) Synthesized FWD Time Records

b) Amplitude Spectra from Synthesized FWD Time Records

Figure 1 - 12 Time domain records and amplitude spectra for synthesized FWD force pulses

The spectral amplitudes for all of the pulses are lower than the peak values in the time domain, because the force energy is distributed over a range of frequencies. The longest duration force pulse (120 msec) has the highest spectral amplitude at low frequencies, but its amplitude drops most quickly with frequency. On the other hand, the shortest duration force pulse (15 msec) has the lowest spectral amplitude at low frequencies, but the highest spectral amplitude at high frequencies. The 120 msec force pulse roughly approximates traffic moving at highway speeds. FWD loading would generally fall somewhere between the 30 and 60 msec force pulses. All three types of FWDs apply the dynamic force to the pavement through a 30 cm diameter circular pad. The KUAB FWD uses an oil-filled hydraulic device to distribute the force equally between four segments in its loading plate. All the devices use a hole in the center of the loading plate to measure the pavement deflections at the point of load application. Load cells are employed to measure the vertical dynamic force applied to the pavement. A linear array of transducers is used to measure the deflection basin from the imposed dynamic loading for all three types of FWDs. The Dynatest FWD uses as many as seven geophones, located at any position in a linear array, to measure displacements. The Phoenix FWD uses three geophones to measure deflections: one at the center of the load pad, and the others at 30 cm and 75 cm from the center of the loading pad. The KUAB uses five specially designed, inertially referenced displacement transducers to measure the induced deflections. The positions of the deflection sensors should be chosen from the following list: 0 - 200 - 300 - 450 - 600 - 900 - 1200 - 1500 - 1800 - 2100 - 2400 mm nevertheless deflection sensors must at least be mounted at the following offsets: 0 - 300 - 600 and 900 mm. The location of other deflection sensors depends on the stiffness of the total pavement structure. The stiffness of the subgrade has a major influence on the deflection bowl shape, and therefore there should be at least two deflection sensors at such a distance from the load centre as to enable the stiffness of the subgrade to be assessed. The ideal deflection sensor locations would be two deflection sensors in each equivalent thickness of the pavement layer. FWD testing is conducted by positioning the FWD at the desired testing location. The loading pad and the deflection sensors are then lowered to contact the pavement. The drop weight is then raised hydraulically. When the drop weight is at the selected drop height, an electrical release drops it onto the loading pad. A data acquisition system measures the load cell and deflection transducer outputs. Typically, the test is repeated several times and the results averaged. Tests can also be performed using different drop heights and, hence, different force levels at each testing location. After the testing is completed, the loading pad and sensors are raised, and the device is towed to the next test location. Typical daily production for the FWD operated by a crew of one or two technicians is 100-300 test locations per day.

1.4 Maximum central deflection and deflection bowl shape characteristics

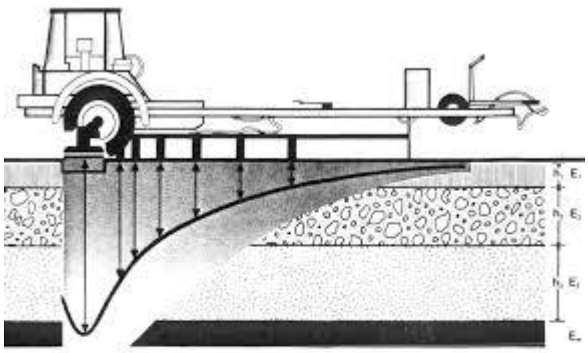


Figure 1 - 13 Deflection bowl shape

The measured deflections obtained, particularly from the FWD, can be used for the determination of the stiffness moduli of the different pavement layers:

- Subgrade
- Road base and subgrade
- Asphalt layer, road base and subgrade

- Cement concrete layer, road base and subgrade.

The backcalculation used to determine stiffness moduli has to be carried out with considerable engineering judgment. If the layers are too numerous or too thin, it is difficult if not impossible to backcalculate stiffness moduli accurately. This is also the case when stiff layers form part of the pavement structure. The backcalculated stiffness moduli derived from FWD measurements can be used:

- to assess the relative contribution of bound and unbound materials to the pavement strength
- to indicate any weak areas that need replacing or special consideration
- to identify the structural quality of a critical layer (or interface)
- to calculate stresses and strains in pavement layers due to the load imposed
- to calculate the estimated (total) pavement life, using the calculated stresses and strains in combination with a fatigue curve or deformation criterion and the traffic history
- to determine the residual pavement life, using the calculated total pavement life and the predicted traffic in the near future
- to calculate the overlay thickness if the residual pavement life is shorter than the required pavement design life.

Once the measured deflection bowl is normalized for load and temperature, the desired deflection bowl parameters can be calculated in fact one common evaluation approach is to compute them from the measured values which are related to the structural strength of different layers. A summary of literature review of existing deflection bowl parameters is listed and described in table:

Indicator	Equation	Unit	Purpose
Centre deflection	D0	μm	Overall pavement condition
Non-central deflection	Dr	μm	Condition of layer at equivalent depth r
Surface Curvature Index, SCI	D0 – Dr	μm	Fatigue of bound layers
Base Damage Index, BDI	Dl – Dr	μm	Condition of base layer(s)
Base Curvature Index, BCI	Dn-l – Dn	μm	Condition of sub-base layer(s)
Curvature Basin Factor, CBF	(D0 – Dr) / D0	-	Condition of layer at equivalent depth r
Deflection Ratio, DR	D0 / Dr	-	Condition of layer at equivalent depth r

Where :

D0 deflection under the base plate

Dr deflection at distance r from the centre of the loading plate

Dn deflection at the outmost deflection sensor

Dn-l deflection at the next to outmost deflection sensor

Dl deflection at the deflection sensor nearest to the loading plate.

1.4.1 Maximum central deflection

The maximum central surface deflection, D0, estimated under the test load axle has traditionally been used as an estimate of the current available pavement/subgrade strength for asset managers, at a network-level and as an assessment of future maintenance/rehabilitation needs for in-service pavements.

The D0 measurement is often compared to given threshold values of D0, which depend on the levels of expected traffic to determine: the current traffic capacity of the pavement and the, remaining pavement life, and as a basis for designing a pavement overlay thickness. The deflection bowl shape is obviously dependent upon the magnitude of the maximum deflection, but it is not solely dependent upon it because different pavement structures will provide, for the same level of D0, different measures of D200, D300 etc.

1.4.2 Deflection bowl shape characteristics

Deflection measurements, other than D0, can provide additional information in conjunction with D0. The surface curvature indices, SCI300 (D0 - D300), SCI600 (D0, - D600) and curvature (D0 - D200) are typically used to provide further information about the pavement and subgrade.

Full deflection bowls can be used to estimate surface layer moduli, a back analysis of layer stiffness, pavement stress and strain and residual pavement life.

For example in the "PARIS project" a model was developed for the moment of crack initiation, defined as the moment of first appearance of at least 0.5 m of cracking in the wheelpaths. According to this study, crack initiation in flexible pavements occurs between the two following numbers of load repetitions.

$$\log(N_{10}) = 7.169 - 0.0074 \cdot SCI_{300} - \frac{2899829}{SCI_{300} \cdot N_{10}Y}$$

$$\log(N_{10}) = 7.287 - 0.0067 \cdot SCI_{300} - \frac{2280264}{SCI_{300} \cdot N_{10}Y}$$

Where:

N_{10} = Cumulative traffic loading at the initiation of cracking (100 kN ESALs)

SCI_{300} = Surface curvature index using a load level of 50 kN, normalised to 20°C

$N_{10}Y$ = Annual number of traffic loading (100 kN ESALs)

By calculating N_{10} from the SCI300 measured between wheelpaths and subtracting the traffic carried already, it is possible to derive a residual number of traffic loads that can still be sustained.

Another example is the result of a research of Dr. Rasmussen of Greenwood Engineering which found a simple relationship between the structural surface index 300 and the asphalt strain at the bottom of the asphalt layer for roads with asphalt layer is thicker than 150 mm.

$$\epsilon = a * SCI_{300}^{b}$$

where:

ϵ =asphalt strain

SCI_{300} = structural surface index

a and b = regression coefficients.

1.5 High performance measures

As traffic densities on many major highways have increased significantly over the last decade throughout most of the world, there is a need to replace traditional stationary or slow moving bearing capacity measurements with high speed measurements. Using stationary equipment like the Falling Weight Deflectometer (FWD) can result in dangerous situations for drivers and the FWD operator, as well as cause congestion.

Another limitation of the existing equipment is the low production of data and the discrete test points are assumed to be representative of a specified length of the pavement under investigation. Several international research efforts are now underway to develop a device that will overcome these deficiencies by measuring the deflections continuously at or at near highway speeds. Many organizations in the USA and Europe have developed devices for this purpose which are in various phases of development, and some of them have been successfully implemented. An example of a high speed device for the acquisition of information on pavement condition is the Traffic Speed Deflectometer (TSD) that is capable of performing continuous bearing capacity measurements at driving speeds up to 80 km/h. Currently, the TSD is the only commercially available tool capable of measuring pavement deflection at traffic speed and it will be described widely in the next Chapter.

Chapter 2
TRAFFIC SPEED DEFLECTOMETER

2.1 Introduction

Perhaps the primary benefit of a continuous deflection measuring device is its ability to provide an overall assessment of the structural condition of the pavement network. Deflection test results can be incorporated into an agency's PMS to support maintenance and rehabilitation strategy scoping and resource allocation decisions, among other asset management business functions.

For these reasons many States use a continuous deflection device for network-level data collection. Within this framework, speed is perceived as a critical characteristic even if it means sacrificing some accuracy. It is important that the results obtained from deflection testing using a continuous deflection measuring device are comparable to static deflection measurements such as those obtained using an FWD. The primary applications of the continuous deflection device at the network level would be to:

- Help identify "weak" (or structurally deficient) areas that can then be investigated further at the project level.
- Provide network-level data to calculate a structural health index that can be incorporated into a PMS.
- Differentiate sections that may be ideal candidates for preservation (quality structural capacity) from those that would likely require a heavier treatment (showing structural deficiencies).

Additionally, some states indicated that they currently use deflection values from FWDs in their PMSs. For example the parameters that have been used by Transport Research Laboratory (TRL) in UK currently use FWD data and are the effective structural number and layer moduli of pavement. In general, the deflection tests were found to be repeatable, successful in identifying problem areas, and generally correlated with FWD test results.

Nowadays, researchers have identified a device as the most promising to deliver the information needed by the users under operating conditions and with high spatial coverage in a relatively short time period: the Traffic Speed Deflectometer (TSD) by Greenwood Engineering. The measurement of pavement deflection before TSD involved the use of sensors in physical contact whit the pavement so this technique could only offer a slow rate of testing and often required additional traffic control measures.

Figure 2 - 1 Anas Traffic Speed Deflectometer

2.2 Description of Traffic Speed Deflectometer

Five TSD devices had been constructed by Greenwood Engineering in Denmark and were in use at the time this thesis was initiated and other two devices were constructed and delivered to USA and China. The first prototype device is owned by the Danish Road Directorate (DRD) and is known as the High Speed Deflectograph (HSD). This tool is operated and researched by the Danish Road Institute (DRI). The second prototype was purchased by TRL in the UK on behalf of the Highways Agency. Originally known as a HSD, this device has been renamed the Traffic Speed Deflectometer. The name change reflects the view that the device does not collect data at high survey speeds, but rather at legal driving speeds for normal traffic. The third one was delivered to Italy and the owner is Anas S.p.A and the others to Poland and South Africa.

Figure 2 - 2 TSDs in the world

The TSD is a rolling wheel deflectometer for measuring pavement deflections at the network level and its design comprises a truck with a 12 tonnes load applied on a rear, dual-tyred, single axle. The velocity of the deflected pavement surface under this load is measured using Doppler laser sensors positioned at different distances from the centre of the load. All sensors are aligned in a single wheelpath.

The Doppler technique is based on the fact that the wavelength of any energy dispersion registered by a moving observer will be phase shifted by a factor (V/c) as described by equation:

$$F_{Doppler} = -F_{Source} \cdot \frac{V}{c}$$

Where V is the relative velocity between source and receiver, c is the wave propagation speed, $F_{Doppler}$ is the frequency shift at the receiver and F_{Source} is the emitted frequency. This principle is illustrated in figure 2-3 which shows that the wavelength of the emitted wave is reduced if the object is approaching and increased if the object is receding.

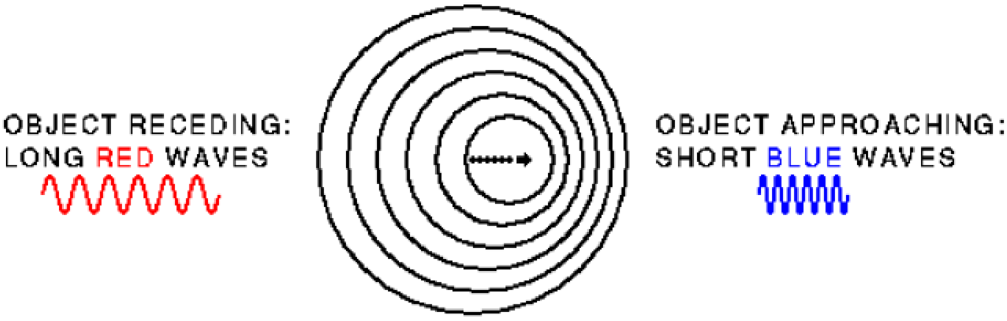


Figure 2 - 3 Doppler principle

Laser rays from the sensors strike the road surface and the sensors measure the velocity in the direction of the laser rays. The sensors are mounted on a rigid beam in front of the right wheel and measure the velocity of deflection due to the load applied by the wheel.

Accelerometers and gyro sensors measure the velocity of the sensors and their angle of incidence with respect to the road. Using this data, the measured velocity is adjusted to account for the motion of the sensors and their angle of incidence with respect to road. The Doppler sensor movements are limited and controlled by a servo system mounted on the beam which assures that the sensors are focused at all times. The servo system is controlled by two distance measuring lasers at the ends of the beam. The adjustments are made using equations:

$$V_{DS} = V_D + V_k \cdot \sin\ \alpha_{DS}$$
$$V_{RS} = V_K \cdot \sin \alpha_{RS}$$

which apply to sensor measuring deflected shape and the reference sensor respectively. Here V_{DS} is the measured velocity, V_D is the deflection velocity, V_K is the driving speed and α_{DS} is the angle of incident of the light from the sensor on the road where an angle of zero corresponds to perpendicular incident. In the second equation, V_{RS} is the velocity measured by the reference sensor, V_K is the driving speed and α_{RS} is the angle of incident of the light from the reference sensor on the road.

The TSD needs to be calibrated before use. The purpose of this calibration is to determine the difference between α_{DS} and α_{RS}. For this purpose, much of the load is removed from the trailer and then measurements are conducted on a very stiff road. It is then assumed that the deflection velocity being zero, the difference between V_{dS} and V_{RS} is solely due to the difference between α_{DS} and α_{RS}. The difference is then assumed to remain constant as the sensors are mounted on a stiff beam.

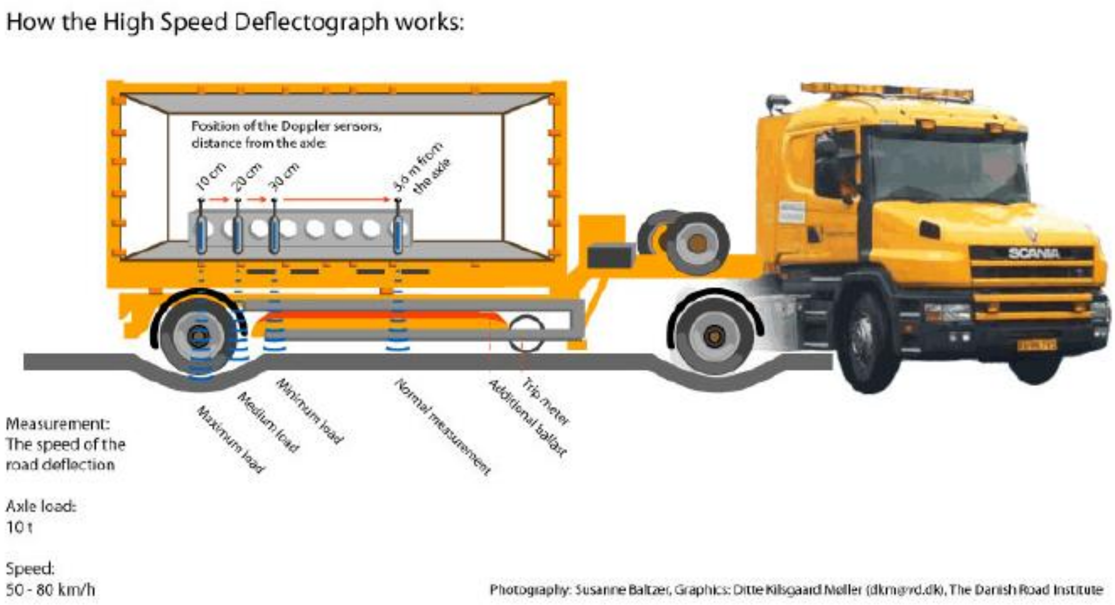


Figure 2 - 4 How the TSD works

The Doppler lasers require a relatively constant velocity input for optimal operation. This cannot be achieved from perfect vertical mounting because most of the velocity measurement would arise from the highly variable vertical suspension movement of the trailer rather than the tiny movement of the pavement. Consequently, the lasers are mounted at an angle of ~2° from vertical as this provides a relatively constant velocity input arising from a component of the vehicle driving speed, which is much larger than the vertical velocities arising from the body movement and pavement deflection velocity.

The collected data is treated in a specialized TSD post-processing software program, TSD for Windows, which outputs base level data such as pavement velocity as well as processed pavement condition indicators.

The device collects deflection readings every millisecond: almost continuously. The use of non-contact laser sensors in the TSD allows the device to collect pavement deflection data at much higher survey speeds and with a need for little to no additional traffic control measures.

This is highly desired by many asset managers, as the deflection data could be used to provide an indication of the structural strength, and future capacity, of entire networks of road pavements. The TSD is therefore considered to have enormous asset management potential.

2.3 Configuration in Italy

ANAS (National Autonomous Roads Corporation) is a whole-of-government owned company. It oversees the entire national road network, which is directly managed by concessionaires. ANAS acts as a concessionaire for 1200 km of the national network.

The TSD owned and operated by ANAS has the following characteristics:

- a 12 tonnes axle load
- seven Doppler lasers (including reference laser)
- the lasers located at 100, 200, 300, 600, 800, 1500 and 3500 mm from the axle load
- a more robust fifth-wheel (based on a motor-cycle wheel) for measuring distance
- isolation, monitoring and conditioning of the temperature inside the trailer
- a new mounting system for the beam which allows a new geometric calibration procedure
- integration of an IRI measuring inertial laser measuring the profile in the same wheel-path as the Doppler lasers
- a high frequency and resolution digital camera
- a GPS referencing system

2.3.1 Sensor location

The Doppler laser sensors are mounted on a rigid beam. The current configuration for this TSD includes Doppler sensors measuring the responses at locations 100, 200, 300, 600, 800 and 1500 mm from the centre of the wheel load. The responses from these lasers are referred to as P100, P200 and P300 etc respectively. The last Doppler laser is termed the reference laser, and its resulting data as P_{ref}. It is positioned 3.5 m ahead of the load. Its data is presumed to be relatively unaffected by the load applied by any of the axles. It is expected to measure negligible vertical pavement deflection velocity and hence its response can be used to remove unwanted vertical velocity signals (arising from driving velocity and vehicle movement) from the measurement lasers.

Continuous data streams of vertical velocity (Vv), horizontal velocity (Vh) and slope (Vv/Vh) are provided for each sensor location.

2.3.2 Laser Angle

As noted previously the lasers are mounted at an angle of approximately 2° from vertical to allow a constant velocity input from the horizontal vehicle speed while having little effect on the vertical speed component.

The lasers cannot be accurately mounted at a precise angle of 2° because of configuration constraints intrinsic to the construction of the laser. The current lasers are not designed and constructed for the purpose of measuring pavement velocity; they have been adapted from existing technology produced for alternative purposes.

If all lasers were mounted at exactly the same angle, corrections for unwanted signals could be made simply by subtracting P_{ref} from the P_x. As this cannot be assumed to be the case, corrections must be take in account of the differences in angle of each measurement laser P_x and the reference laser P_{ref}. The correction must be made to a high degree of precision as an error in angle of only 0.005°

could produce a 25% error in the final results. The process for determining laser angles is known as geometric calibration.

2.3.3 Speed

The TSD operates reliably at up to 80 km/h with a minimum operating speed of 40 km/h. Performance above 80 km/h has been shown to be significantly affected by uncertainty. ANAS standard operating procedure requires data collection at 60-80 km/h; this is principally to enable data collection at the same operating speed throughout the network and to minimize the effect of adverse factors at higher speeds.

2.3.4 Load level

The standard operating load on the rear axle of the TSD is 12 tonnes which is the maximum acceptable load on Italian road. In its routine operation the TSD does not measure dynamic load directly. However, strain gauges had been fitted to the rear axle of the trailer for a previous investigation, and they were used to obtain dynamic wheel loads.

2.3.5 Temperature control

The container on the TSD has recently had air-conditioning and fans installed in response to the sensitivity to absolute temperatures and temperature differentials in the beam that had been discovered by TRL on the UK TSD.

Investigations by TRL into temperature-related repeatability impacts showed that temperature had an effect on the value of the deflection slope recorded. TRL had noted that the Doppler laser units generate sufficient heat to locally affect the temperature of the rigid beam. It was believed that the resulting temperature gradients distorted the beam enough to change the relative laser angles and so affect the reliability of the data collected.

TRL installed air-conditioning and fans within its device and believes that temperature differential effects related to the beam moving are now controllable. The same system was installed in the Italian TSD.

2.4 Data Interpretation

Compared to other strength-measuring devices, the TSD collects a very large amount of data in a continuous stream such that:

- continuous data streams of vertical velocity (Vv), horizontal velocity (Vh) are provided for each sensor location
- for each 0.02 m travelled the system provides deflection velocity information that compares to a resolution of 5 μm
- data volume is approximately 6 megabytes per measured kilometer (dependent upon driving speed)
- approximately 1000 data samples are recorded per second per sensor.

The machine data from the lasers is processed within the Greenwood software program TSD for Windows to correct for variance associated with the laser positioning inclusive of mounting angle, location etc.

Corrected laser data can be interpreted and further processed. Mechanisms currently are illustrated in figure 2-5 state that mathematical modelling and integration values for differences in deflection between the lasers can be used to infer the deflections at any location within the deflection bowl.

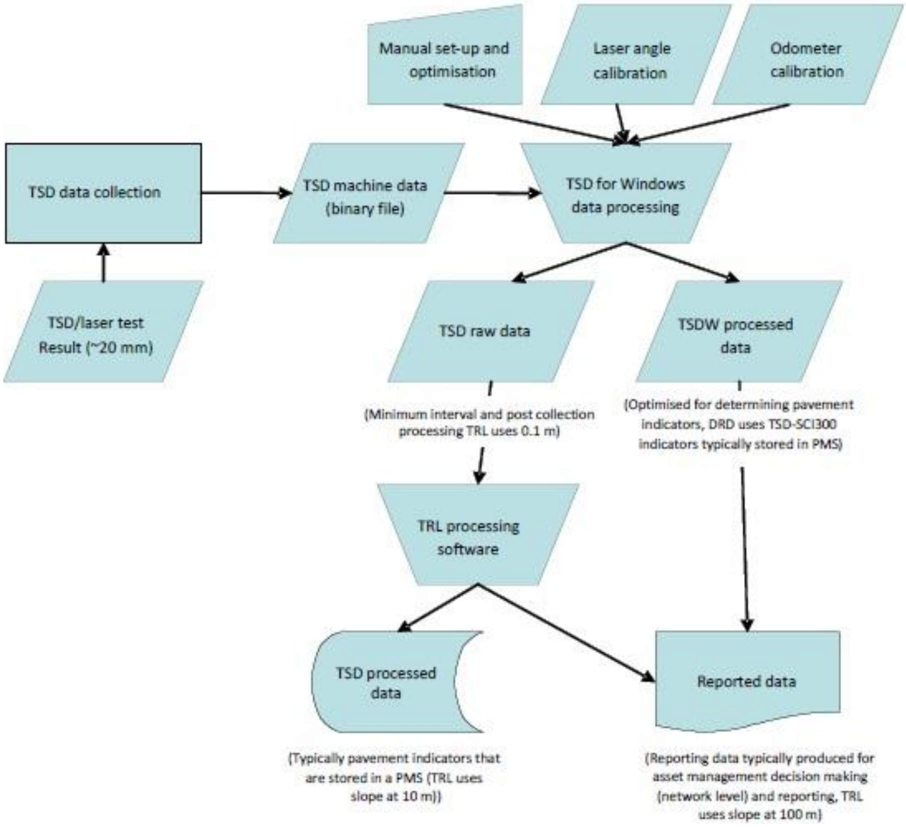


Figure 2 - 5 Data capture and processing paths

2.4.1 Analysis methodologies

A key issue in using the TSD device is the approach used to determine deflection measurements from the measurements of vertical pavement velocity collected by Doppler lasers. The following section reviews existing methodologies outlined in the literature and derives the key relationships.

2.4.2 Existing methodologies

In an earlier work, Hildebrand et al. (1999, 2000)[1] describe fitting a sixth-order polynomial curve fit to FWD deflection bowl measurements and determine the profile of velocity data as the first derivative of this curve fit, for a given driving

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[1] Hildebrand, G., Rasmussen, S., Andrés R., 1999. "Development of a Laser Based High Speed Deflecto-graph. Nondestructive Testing of Pavements and Backcalculation of Moduli". Third Volume, ASTM STP 1375, West Consho-hocken, PA.

speed. In the 1999 report, the authors note that the Doppler lasers provide information about the slope of the deflection bowl at the measured point on the ground, but do not derive this relationship. Later, Hildebrand and Rasmussen (2002)[2] described an approach of curve fitting multiple measured deflection velocity points and integrating the fit to produce the absolute deflection profile, illustrated with a plot of measured deflection velocities versus position in basin.
Krarup et al. (2006)[3] described a method of curve fitting TSD measurements of pavement slope arising from a two parameter model consisting of an elastic beam on a Winkler foundation model.

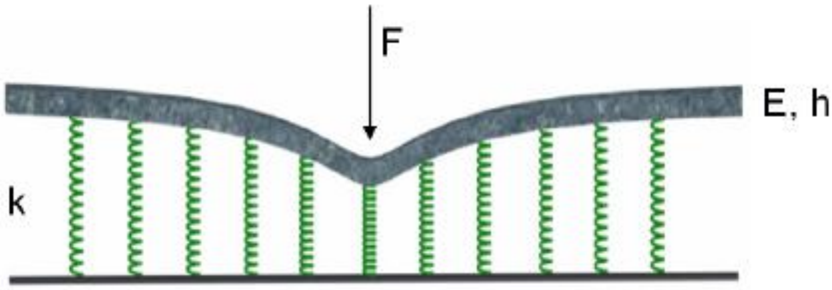

Figure 2 - 6 Deflection basin from a point load on a Winkler foundation model

Constants within the model are adjusted to achieve the best fit between slope predicted by the model and the TSD pavement slope measurements. These optimized constants are then substituted into the explicit integral of the slope equation arising from the model with respect to wheel offset to generate the deflection profile. Rasmussen et al. (2008)[4] further described the modeling approach, stating that it is based on a Euler–Bernoulli beam equation and noting

[2] Hildebrand, Gregers, Rasmussen, Søren, 2002. "Development of a High Speed Deflectograph, Road Directorate". Denmark, 2002

[3] Krarup, J., Rasmussen, S., Aagaard, L., 2006. "Output from the Greenwood traffic speed deflectometer". ARRB conference, 22nd, Canberra

[4] Rasmussen, S., Aagaard L., Baltzer, S., Krarup, J., 2008. "A comparison of two years of network level measurements with the traffic speed deflectometer". Transport research arena Europe 2008, Ljubljana, Slovenia.

that the results are only reliable in the vicinity of the measurement points near the wheel load.

Bearing Capacity Characteristics derived from a Point Load F on an elastic beam with Elasticity E and thickness h. k is the spring constant of the foundation.

$$\begin{aligned}
&\text{Deflection} &:&\quad d(x) &=&\quad -\tfrac{A}{2B}\big(\cos(Bx)+\sin(Bx)\big)\mathrm{e}^{-Bx}\\
&\text{Deflection Slope} &:&\quad d'(x) &=&\quad A\sin(Bx)\mathrm{e}^{-Bx}\\
&\text{Curvature} &:&\quad d''(x) &=&\quad AB\big(\cos(Bx)-\sin(Bx)\big)\mathrm{e}^{-Bx}\\
&\text{Elasticity} &:&\quad E &=&\quad \tfrac{3\sqrt{2}F}{4h^3}\cdot\tfrac{1}{AB^2}\\
&\text{Stiffness} &:&\quad k &=&\quad \tfrac{\sqrt{2}F}{AB}
\end{aligned}$$

$$\begin{aligned}
&\text{Maximum deflection} &:&\quad d(0) &=&\quad -\tfrac{A}{2B}\\
&\text{Structural Curvature Index 300} &:&\quad \mathrm{SCI}_{300} &=&\quad d(0)-d(300)\\
&\text{Maximum Slope} &:&\quad d'(\tfrac{\pi}{4B}) &=&\quad \tfrac{\mathrm{e}^{-\pi/4}}{\sqrt{2}}A\\
&\text{Curvature under the wheel} &:&\quad d''(0) &=&\quad AB
\end{aligned}$$

These functions are defined for $x \geq 0$, $A > 0$ and $B > 0$. A and B are constants to be optimized.

Figure 2 - 7 Family of functions proposed by European Study Group with Industry (ESGI)

2.4.3 Surface Curvature Index (SCI)

Danish and Italian researches are focused on the estimation of the surface curvature index SCI300. This is the difference between the maximum deflection directly under an applied load (D0) and the deflection measured 300 mm from the load (D300).

SCI300 is not directly measured by the TSD, but rather it is mathematically estimated.

2.4.4 Slope

On behalf of the UK Highways Agency, TRL obtained the second commercial production prototype TSD from Greenwood Engineering in 2005. Since its purchase, TRL has undertaken a comprehensive program of research and evaluation of the TSD and its application to the UK highway and motorway network.

UK highway engineering standards do not make use of deflection curvature and as a result TRL literature has focused less on the estimation of SCI300, and instead reported most data in terms of the slope of the velocity data from a single laser measure. As shown in figure 2-8, this is the ratio of the vertically measured velocity of the deflected pavement (Vv) and the instantaneous survey or horizontal speed of the vehicle (Vh). Slopes can be determined from any of the Doppler laser sensors. In this report slope measurements are reported based on their position i.e. slope from P100 is reported as S100.

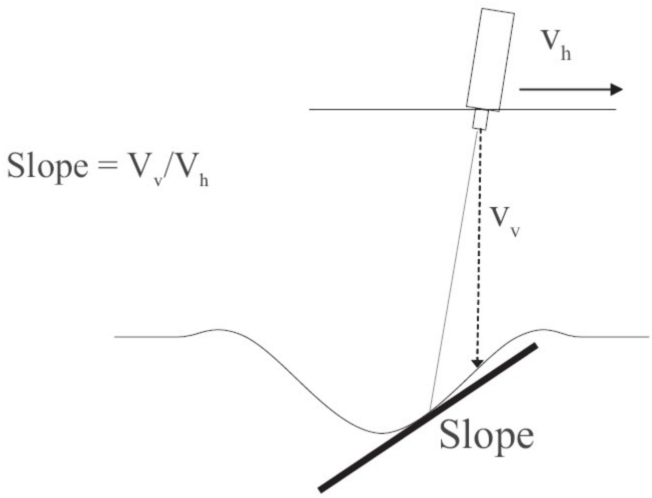

Figure 2 - 8 Definition of slope

2.4.5 Maximum Deflection (D0)

Traditional deflection measuring using contact devices routinely produce a value of maximum deflection (D0) located directly below the applied load. Benkelman beams, deflectographs and falling weight deflectometers all measure this parameter. The configuration of deflectographs, falling weight deflectometers, and some Benkelman beams, allow the determination of deflections at additional locations allowing the measurement of a deflection bowl.

The TSD, in its simplest set-up with a tight array of Doppler lasers near the centre of maximum deflection, provides an estimate of the shape of the seat of the deflection bowl (i.e. its curvature). However, the TSD cannot measure maximum deflection. By definition the location at which the maximum deflection occurs must have zero vertical velocity.

Baltzer (2009)[5] states that TSD data from various laser positions can be interpreted to derive a very accurate shape of the seat of the deflection bowl.

2.5 Data rate

The laser light reflected back from the pavement is subject to a certain amount of scatter. This, in combination with recording and processing limits of the equipment, means only a proportion of the laser response to the pavement is recorded. The TSD collects data at the rate at which acceptable data is received by the lasers, termed the "data rate" (Ferne et al. 2009b)[6]. A high data rate signifies a high rate of meaningful data capture, whereas a decrease in data rate progressively indicates increasingly unsatisfactory data capture by the TSD.

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[5] Baltzer, S., 2009. "Three years of high speed deflectograph measurements of the Danish state roads network". International Conference on the Bearing Capacity of Roads, Railways and Airfields, Urbana, Illinois, USA.

[6] Ferne, B., Langdale, P., Round, N., Fairclough, R., 2009b. "Development of the UK highways agency traffic speed deflectometer". International Conference on the Bearing Capacity of Roads, Railways and Airfields, Urbana, Illinois, USA.

In regard to the data rate produced by the TSD, Roberts and Byrne (2008)[7] found the following:

- The Doppler lasers produce about 4000 data samples per second.
- Of all these potentially valid samples, the sensors are currently configured to take a maximum of some 1200 per second, which is usually adequate.
- There is a typical loss of 200 samples per second due to scatter and other effects leaving a useable data rate of 1000 per second of valid data. Thus, for a vehicle speed of 20 m/s (72 km/h), this is typically one valid reading per sensor for every 20 mm along the road.
- The processing software is defaulted to reject data if the data rate is less than 750 samples per second.
- TRL has found that if the rate is less than 900 per second, the overall data quality starts to decline. This has been found to be strongly influenced by roughness.

TRL has used the data rate as an indicator of the effect of external influences on the performance of the UK TSD. For example, changes in data rate have been noted to correlate with changes from concrete surfaces to bituminous ones. One significant observation was the very low data rate obtained when testing a new bituminous (presumably hot mix asphalt) surface.

TRL has observed that drops in data rate are generally reflected in a corresponding drop in measured deflection.

[7] Roberts, J., Byrne, M., 2008. “An initial review of Greenwood traffic speed deflectometer (TSD) and its potential applicability for the RTA”. Contract report, ARRB Group, Vermont South, Vic.

2.6 Specification for continuous deflection measurement

A continuous measurement device shall be provided that is capable of scanning road network bearing capacity and to point out locations with bearing capacity deviations and thus minimize use of traditional stationary or slow moving equipments. The device shall be able to perform well at traffic speeds of 50 km/h or higher.

The sensor for deflection shall be a Doppler laser that can measure deflection velocity of the pavement surface. The device shall employ a reference sensor to remove unwanted contributions in the measurement. The equipment shall be modular in the sense that it may be synchronized in a digital network with other software packages like “Profilograph”, “Pavement LineScan Video”, “Right-of-Way Video”, “GPS” or TMV.

2.6.1 Sensor Specifications

The device shall consist of Doppler sensors which shall be placed 100 mm apart in front of the moving load. One of them shall be placed outside the deflection bowl as a reference. The Doppler sensors shall meet the following specifications:

Sensor head:

- Laser type: helium neon
- Wavelength: 633 nm or better
- Laser safety class: II
- Operating temperature: 0°C/40°C
- Storage temperature: -15°C/65°C

Signal processing:

- Calibration error: < 0.1%
- Data rate: max. 2000 measurements/s (internal, without averaging)
- Signal delay: < 5 ms (measured at the analog output)

- Power consumption: max. 100 VA
- Operating temperature: 5°C/40°C
- Storage temperature: -15°C/65°C

Overall System specification:

- Accuracy: 5x10^{-6}m or better
- Precision: 2x10^{-5} m or better
- Resolution: 10^{-5}m or better
- Driving Speed: 70 km/h

2.6.2 Other Sensor Specifications

The sensors other than velocity sensors shall meet the following criterion:

Odometer:

The device shall include an Odometer which has an accuracy of 0.01% or better. The Odometer shall perform under the following operational/environmental conditions:

- Shock 100 g, 11 ms
- Vibration 10 g (10 to 2000 Hz)
- Temperature -20°C/85°C
- Accuracy Resolution: 20.000 pulses per rotation o rotational error: <0.2 pulse

Gyroscope:

The device shall be provided with Gyroscope which provides digital output and meets the following operational/environmental conditions:

- Shock: 30 g, 11 ms
- Vibration: 0.1 g2/Hz, 1 h/axis
- Temperature: -40°C/65°C

- Accuracy:
  - Measuring range ±100 E/s
  - Random walk < 0.5 E/ *h*
  - Output data rate 125 Hz
  - Scale factor < 0.3 % (1 σ)

2.6.3 Accelerometer (vertical)

The device shall consist of an accelerometer to measure vertical movements and shall be a Closed-loop force balance type with pivot-and-jewel bearing. The accelerometer shall meet the following operational/environmental requirements:

- Shock survival: 100 g - 11 ms shock survival
- Operating temp: -55°C/95°C
- Storage temp: -65°C/95°C
- Accuracy:
  - Resolution: 5 µg
  - Bandwidth: 150 Hz
  - Damping ratio: 0.6
  - Linearity error: < 0.5 mg
  - bias drift: < 20 µg per EF

Data Acquisition System:

The system shall be equipped with the data-acquisition system capable to capture and handle output from all sensors and instruments. In addition, the device shall have a rack to properly accommodate power supply electronics, interface electronics for signal conditioning and an industrial computer. The data-acquisition software and software for post-processing of data shall be provided.

2.6.4 Calibration

A calibration procedure and necessary equipment shall be provided by the manufacturer for calibration of the equipment. In addition, the design requirements for calibration slabs (if needed) shall be provided by the manufacturer before the delivery of the equipment.

2.6.5 Availability of Spare Parts

The manufacturer shall provide availability of any spare parts for the device for at least 5 years from the date of acceptance of delivery.

2.6.6 Warranty and Documentation

The system shall be warranted to be free from defects in materials and workmanship for a period of one year from the date of acceptance of delivery. During training five sets of Operator's Guide, Software Manual and Technical Reference containing drawings, detailed diagrams and cabling tables etc. shall be provided.

2.6.7 Training

The necessary training shall be provided to a minimum. The training shall include demonstration of the equipment, data analysis, calibration of the equipment, and how to trouble shoot in case of problems both in terms of operation and data analysis. The training shall be provided along with the delivery of the equipment.

Chapter 3
STATE OF THE ART

3.1 Introduction

As the TSD is a newly developed innovative device there is only limited publicly available information relating to its performance, and some of its fundamentals of operation.

Summarized below are various aspects of TSD performance that have been investigated and evaluated. The information presented in this section represents the best understanding of the issues and status of TSD technology as at 2013.

3.2 Validation of the location referencing system and distance measurement

TRL validated the location referencing and distance measurement as part of its acceptance tests for the UK TSD. TRL found the odometer wheel and the photocell trigger consistently read to within +/- 1 m (Ferne et al. 2009b)[8]. Due to configuration constraints the odometer wheel (5th wheel) is not located in the same wheel path as the loading wheel. This contributes to an inaccuracy of measurement at bends. However, this is a practical constraint and from a survey perspective it is likely this variation would be managed through location referencing procedures and acceptance criteria.

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[8] Ferne, B., Langdale, P., Round, N., Fairclough, R., 2009b. "Development of the UK highways agency traffic speed deflectometer". International Conference on the Bearing Capacity of Roads, Railways and Airfields, Urbana, Illinois, USA.

3.3 General repeatability testing

A variety of studies on the TSD have demonstrated the short-term repeatability of the results produced by the device (Baltzer 2009, Ferne et al. 2009b, Jenkins 2009, Krarup et al. 2006, Rasmussen et al. 2008, Rasmussen & Hildebrand 2002, Rasmussen, Krarup & Hildebrand 2002, Simonin et al. 2005)[9]. The TSD shows very good repeatability in the short-term under the same operating and environmental conditions (i.e. vehicle speed and temperature). Most testing into repeatability, including TRL's acceptance testing (Ferne et al. 2009b), has involved repeated runs in close time proximity (one after another) at the same speed to reduce the influence of other parameters on results. Figure 3-1shows an example of the repeatability results produced by TRL. Confident that the concept and technology is proven, both TRL and DRD have been exploring the influence of other factors on repeatability such as vehicle speed, temperature and axle load with a view to developing correction factors to produce consistent data regardless of conditions at the time of data capture.

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[9] Baltzer, S., 2009. "Three years of high speed deflectograph measurements of the Danish state roads network". International Conference on the Bearing Capacity of Roads, Railways and Airfields, Urbana, Illinois, USA.

Ferne, B., Langdale, P., Round, N., Fairclough, R., 2009b. "Development of the UK highways agency traffic speed deflectometer". International Conference on the Bearing Capacity of Roads, Railways and Airfields, Urbana, Illinois, USA.

Jenkins, M., 2009. "Geometric and absolute calibration of the English Highways Agency traffic speed deflectometer". Young researchers seminar, Torino, Italy, European Conference of Transport Research Institutes (ECTRI), Bron, France

Krarup, J., Rasmussen, S., Aagaard, L., 2006. "Output from the Greenwood traffic speed deflectometer". ARRB conference, 22nd, Canberra.

Rasmussen, S., Aagaard L., Baltzer, S., Krarup, J., 2008. "A comparison of two years of network level measurements with the traffic speed deflectometer". Transport research arena Europe 2008, Ljubljana, Slovenia.

Rasmussen, S., Hildebrand, G., 2002. "Development of a high speed deflectograph". Report 117, Road Directorate, Danish Road Institute, Roskilde, Denmark.

Rasmussen, S., Krarup, J.A., Hildebrand, G., 2002. "Non-contact deflection measurement at high speed". In AG Correria & FEF Branco (eds), International conference on the bearing capacity of roads, railways and airfields, 6th, Lisbon, Portugal.

Simonin, J.M., Lièvre, D., Rasmussen, S., Hildebrand, G., 2005. "Assessment of the Danish high speed deflectograph in France". International conference on the bearing capacity of roads, railways and airfields, 7th, Trondheim, Norway.

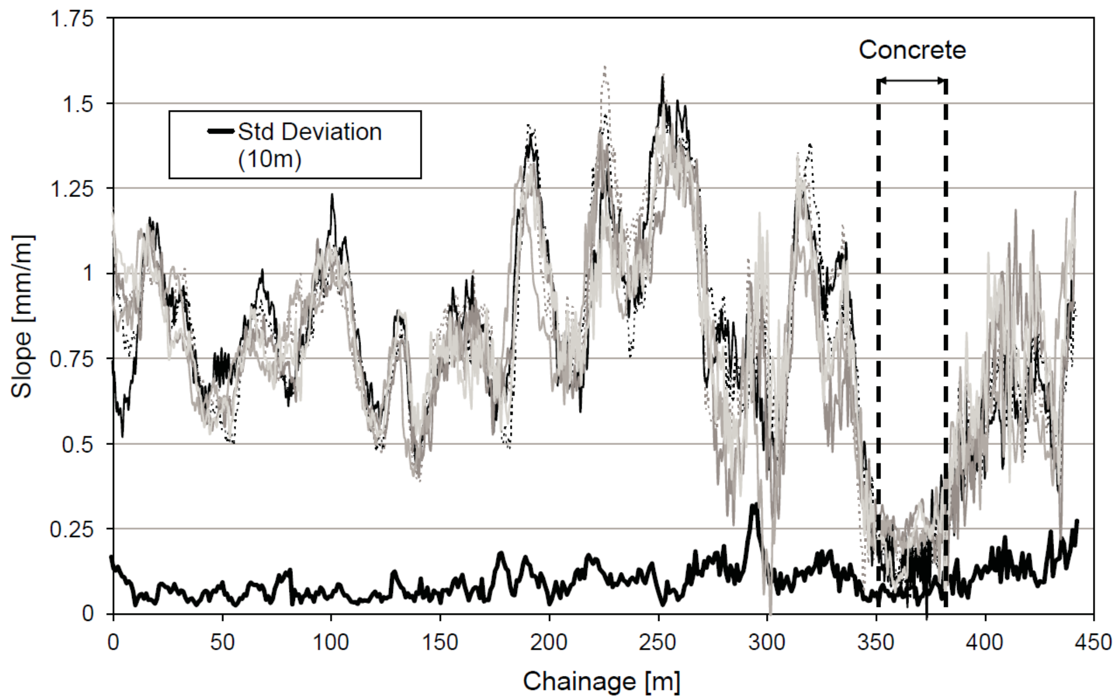

Figure 3 - 1 Repeatability of deflection slope at 70 Km/h

DRD has been collecting TSD data at the network level for over three years and has found that at the network level the TSD shows very good repeatability in its ability to detect variations in the structural performance of pavements (Baltzer 2009)[10]. Examination of data collected over successive years on selected road sections showed a similar variation in TSD SCI300 profile and that those profiles compared well with the SCI300 profile calculated from FWD measurements. The analysis of trial data of RTA (Roads and Traffic Authority) in Australia in 2011 supported the consistence of results over a short period (figures 3-2, 3-3 and 3-4).

[10] Baltzer, S., 2009. "Three years of high speed deflectograph measurements of the Danish state roads network". International Conference on the Bearing Capacity of Roads, Railways and Airfields, Urbana, Illinois, USA.

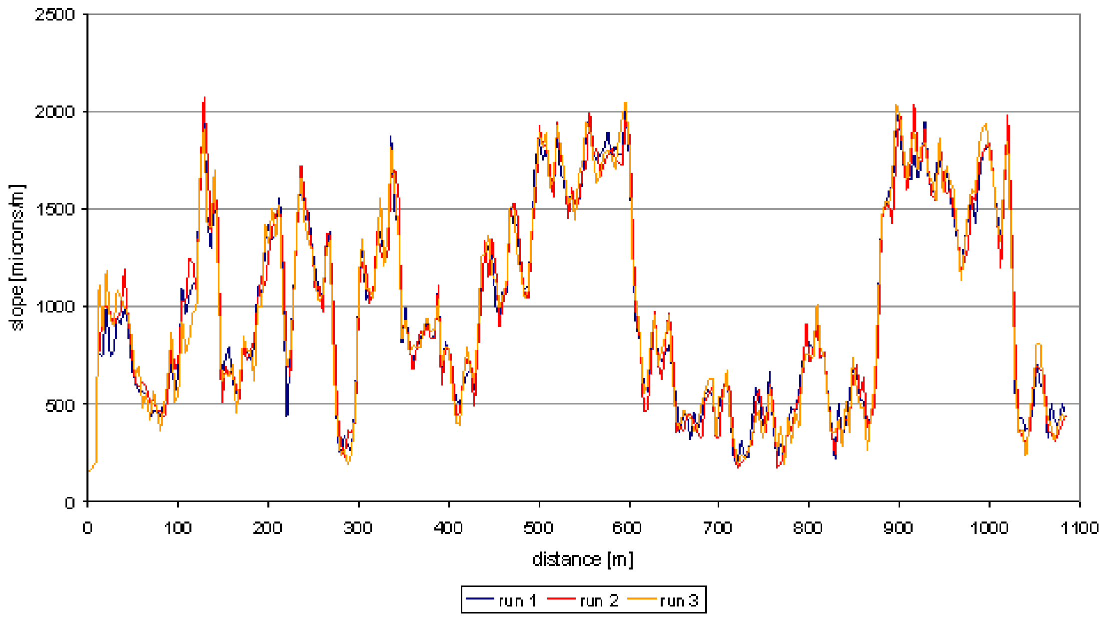

Figure 3 - 2 Same day short-term repeatability – TSD slope values measured at 60 Km/h at Illawarra

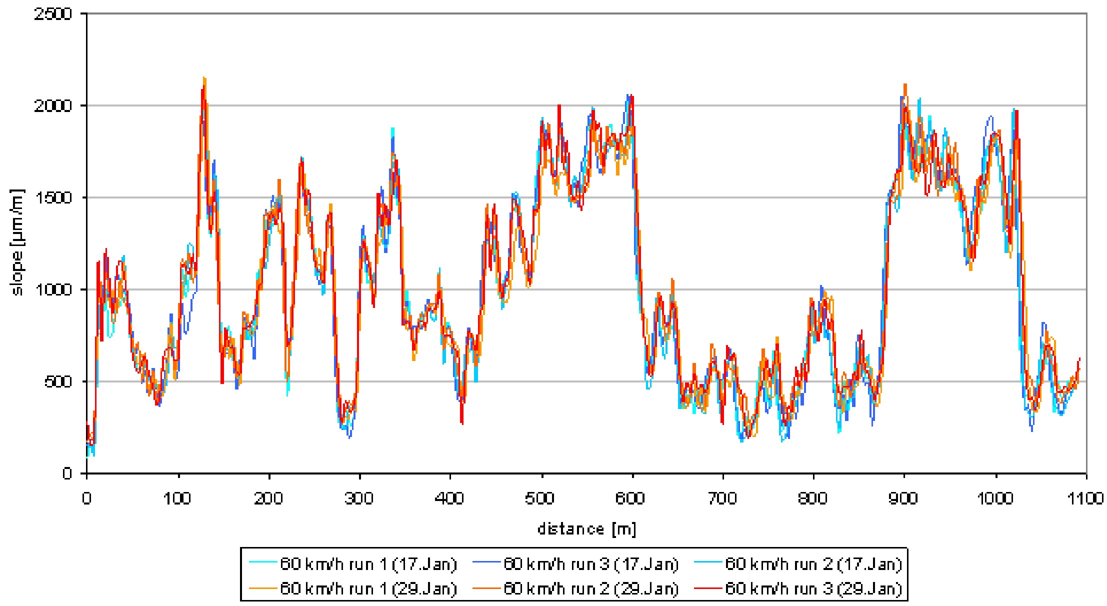

Figure 3 - 3 Short-term repeatability over a 2 week period – TSD slope values measured at 60 Km/h at Illawarra

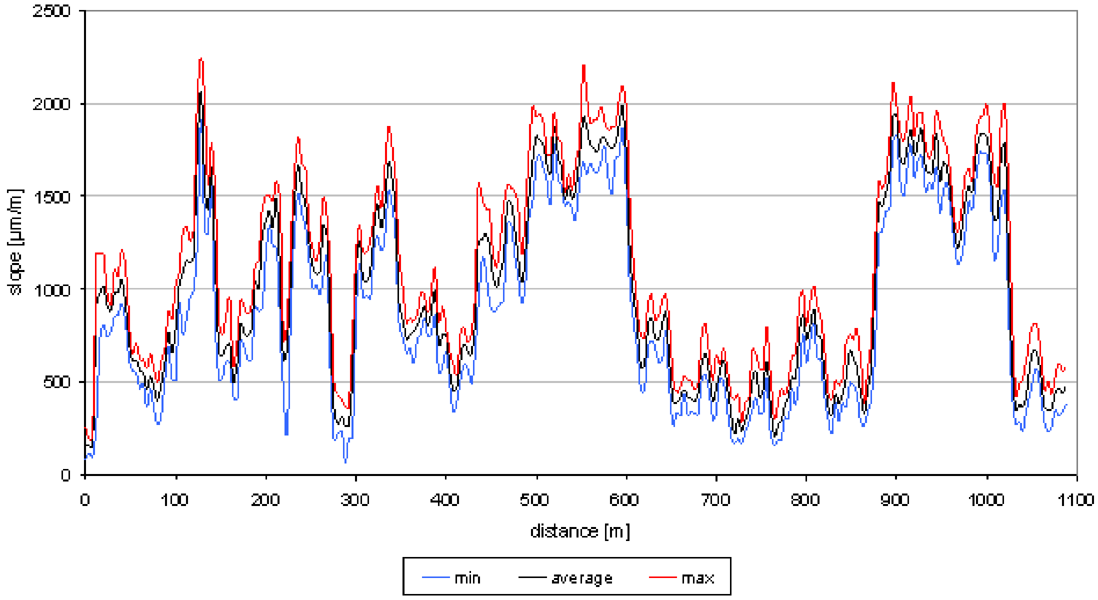

Figure 3 - 4 Short-term repeatability – TSD slope values measured at 40, 60, 80 Km/h at Illawarra

On a more detailed scale it was observed that in the trials there was a shifting of chainage between several runs, i.e. that distinctive peaks measured in one run occur at a location of up to (but apparently no more than) ± 8 m in another run. It was also observed that the shift in chainage was not always constant along an entire measured section. The variation may be due to difficulties in matching test run start points, influences of the distance measuring fifth wheel, or to a combination of these issues.

Advice from TRL indicated that UK testing had found that longer-term repeatability of the UK TSD was less reliable. Although the profile shape remained consistent, TRL advised it had observed inexplicable increases or decreases in the magnitude of UK TSD results.

Examples of the Australian testing into the longer-term repeatability of TSD measurements are shown in figures 3-5 and 3-6.

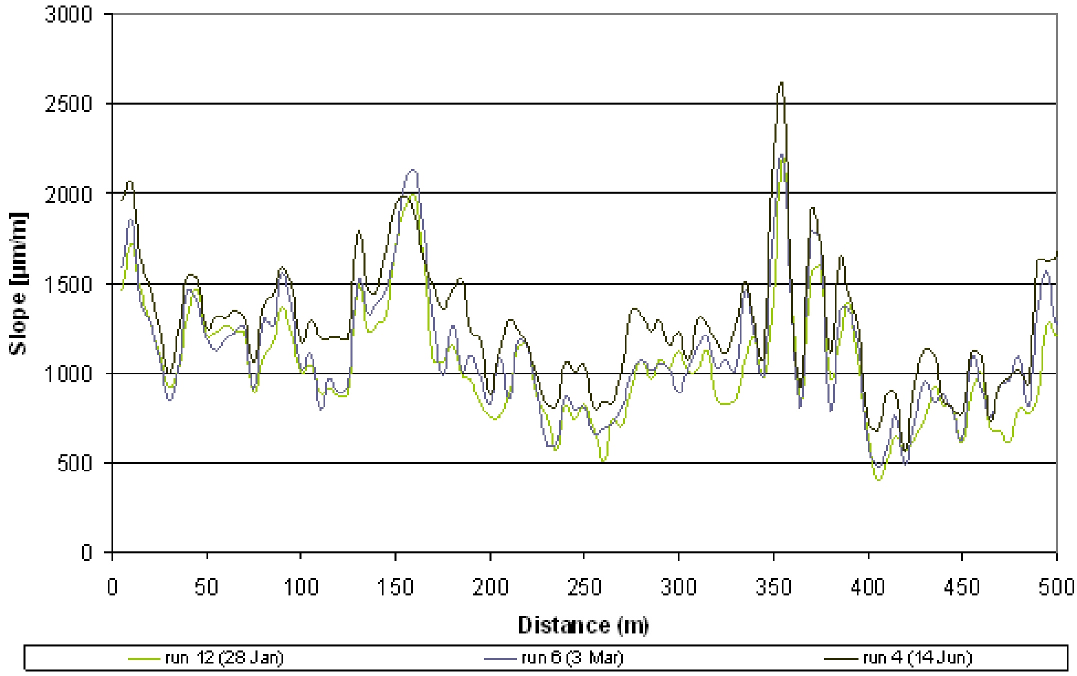

Figure 3 – 5 Long-term repeatability – TSD values measuerd at Oolong

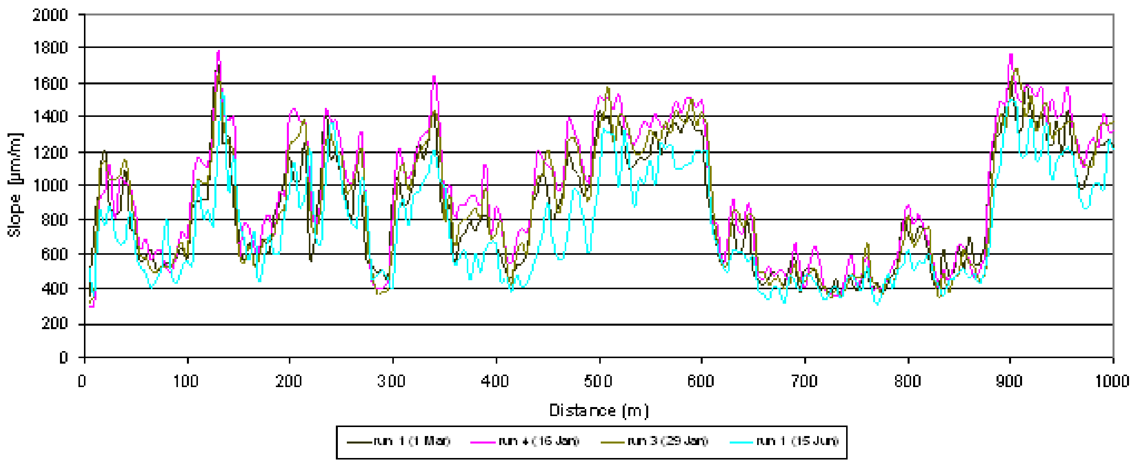

Figure 3 – 6 Long-term repeatability – TSD slope values measuerd at Illawarra

Test results from four different surveys taken over a six-month period at Oolong and Illawarra illustrate the repeatability of the TSD over a longer period. The response profile is consistent over the time period but there is a discrepancy between the results from different survey dates that is most noticeable in the June results. At Illawarra the June results are measured at the same survey speed (70 km/h) as previous surveys and are at lower magnitude than the results from previous surveys.

As with the UK studies it would seem longer-term repeatability is less reliable; however, it should be pointed out that the data used in this analysis was not captured in a controlled environment and consequently environmental factors (like the ambient road temperature) could influence the response of the pavement. Given the consistency in the measurement profile and short-term repeatability on the day, it is probable the variation is related to environmental or operational factors.

3.4 Factors affecting repeatability

3.4.1 Ambient and road surface temperature

Baltzer (2009) describes how, in April 2007, the DRD took advantage of a project-level FWD assessment of a section of motorway that needed rehabilitation to investigate temperature effects. On the same day the FWD tests were carried out, the DK TSD collected data on the same section of road, three times before 10 am and twice after 2 pm. The measured values showed good repeatability of TSD SCI300 calculated from the TSD (Figure 3-7). There was a slight increase in average TSD SCI300 detected over the day that reduced on the last run and Baltzer noted that this was possibly related to the temperature of the asphalt layer.

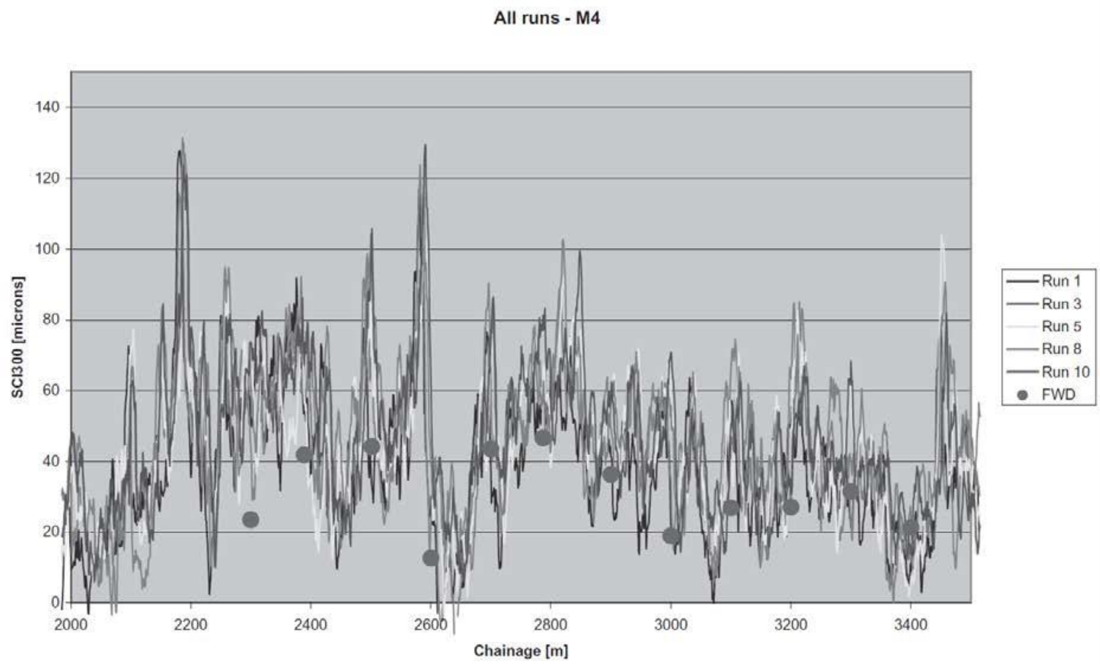

Figure 3 – 7 TSD and FWD measurements taken on the same day

The study into the three years of TSD data by DRD (Baltzer 2009) showed there was a shift in TSD SCI300 values from year to year. The sections studied indicated a decrease from one year to another year of 5-10 microns. DRD thought the temperature of the asphalt layer may have influenced the results.

From the literature available it would appear that TRL is the group that has undertaken the most detailed investigation into the effect of temperature on the performance of the TSD. In 2006 when it was clear to TRL that temperature did affect the value of the deflection slope recorded by the TSD, it was still unclear if this was because of its effect on the road, the equipment or both (Ferne et al. 2009a)[11].

At low ambient temperatures, and hence low temperatures of the measurement beam, the data rate was found to decrease significantly and there was a corresponding drop in deflection slope. TRL thought the cold measurement beam

[11] Ferne, B., Langdale, P., Round, N., Fairclough, R., 2009a. "Development of a calibration procedure for the UK Highways Agency traffic speed deflectometer". Transportation Research Record, no. 2093, London, UK.

may have prevented the lasers from reaching their correct operating temperatures (Ferne et al. 2009b). TRL initially restricted data for reliability testing to that collected where ambient temperatures were above 15 °C.

Further investigation showed that as the lasers heated up they were causing temperature gradients of up to 4 °C in the measurement beam itself. The temperature gradients were sufficient to cause recorded differences in the deflection slope by distorting the measurement beam. In March 2008 TRL installed two fans in its device and the development of temperature gradients were virtually eliminated. Subsequently, a full climate control system was fitted to the UK TSD in late 2008 allowing the absolute temperature of the beam to also be controlled. The UK TSD now operates with a beam temperature of 20 °C +/- 0.5 °C with no operating constraints on ambient temperature. Initial findings suggested that repeatable results were obtained over pavement temperatures ranging from 9 °C to 36 °C. The TRL work demonstrated that temperature variations influence the measurement equipment and hence the measured pavement response is compromised. TRL appears to have solved these problems, at least for the temperature ranges that are experienced in the UK, by controlling the temperature of the equipment. Temperature differences can also affect the behavior of the pavement being tested. The stiffness of bitumen is dependent upon its temperature, and therefore the magnitude of deflections measured on asphalt is dependent upon the temperature of the asphalt. The higher the temperature, the lower the stiffness and the higher the deflections. It is common practice to standardize recorded deflections taken at varying asphalt temperatures to a representative temperature for the pavement being tested (Austroads 2009b)[12]. The standardization processes vary between established testing devices (Austroads 2009d)[13], and so it is expected that appropriate methods need to be determined for the TSD.

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[12] Austroads, 2009b. "Guide to pavement technology: part 1: introduction to pavement technology". AGPT01/09,Sydney, NSW.

[13] Austroads, 2009d. "Guide to pavement technology: part 5: pavement evaluation and treatment design". 2nd edn, AGPT05/09, Sydney, NSW.

In 2011 RTA investigated into the possible influence of temperature on TSD measurements, average temperature values were plotted against slope values and a simple linear regression was performed. This analysis is shown only to highlight that temperature may influence the slope measurement.

There appears to be some correlation between ambient temperatures, the response of the pavement and the TSD measurement system as shown in figure 3-8. No other environmental characteristics were considered.

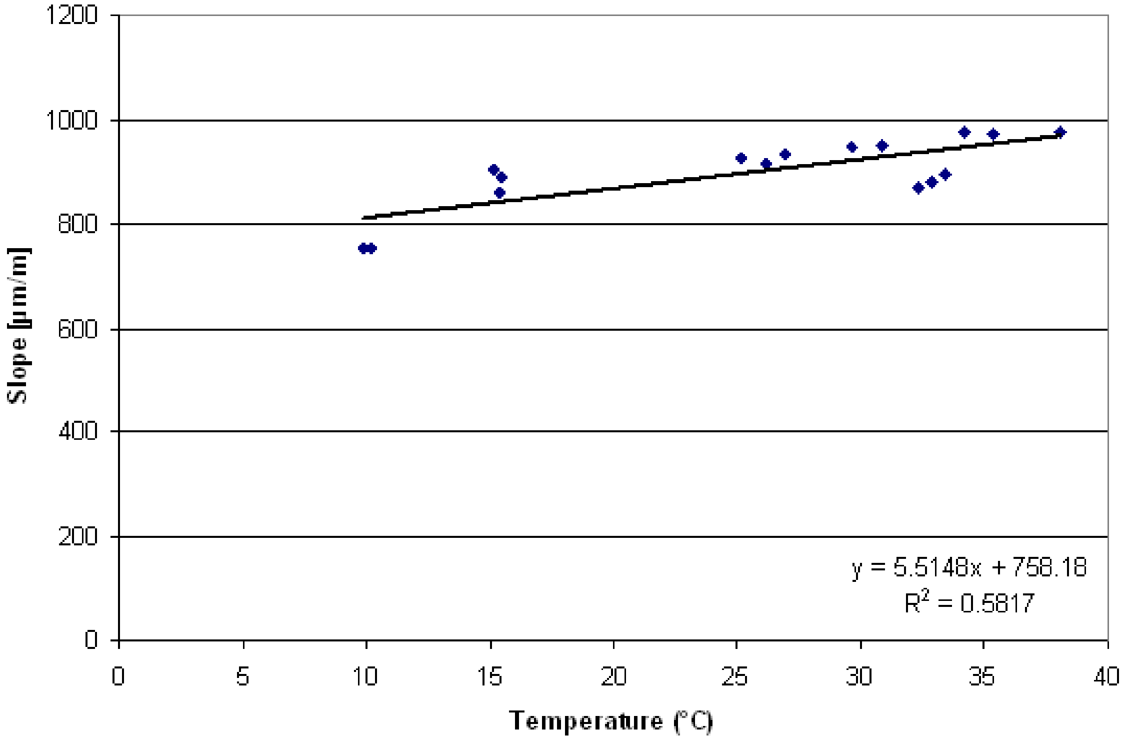

Figure 3 – 8 Slope vs. road temperature at Illawarra

In Italy, for each type of work (new constructions NC, deep rehabilitations (RP) and surface rehabilitations (RS)), ANAS assessed the characteristics of bearing capacity, and therefore the deflection bowls, which were obtained with a given load (1700 kPa) and certain materials.

These calculations allowed to determine the allowable limits for the SCI300 in function of the test conditions and were reported in a series of graphs in the technical standards (figure 3-9).

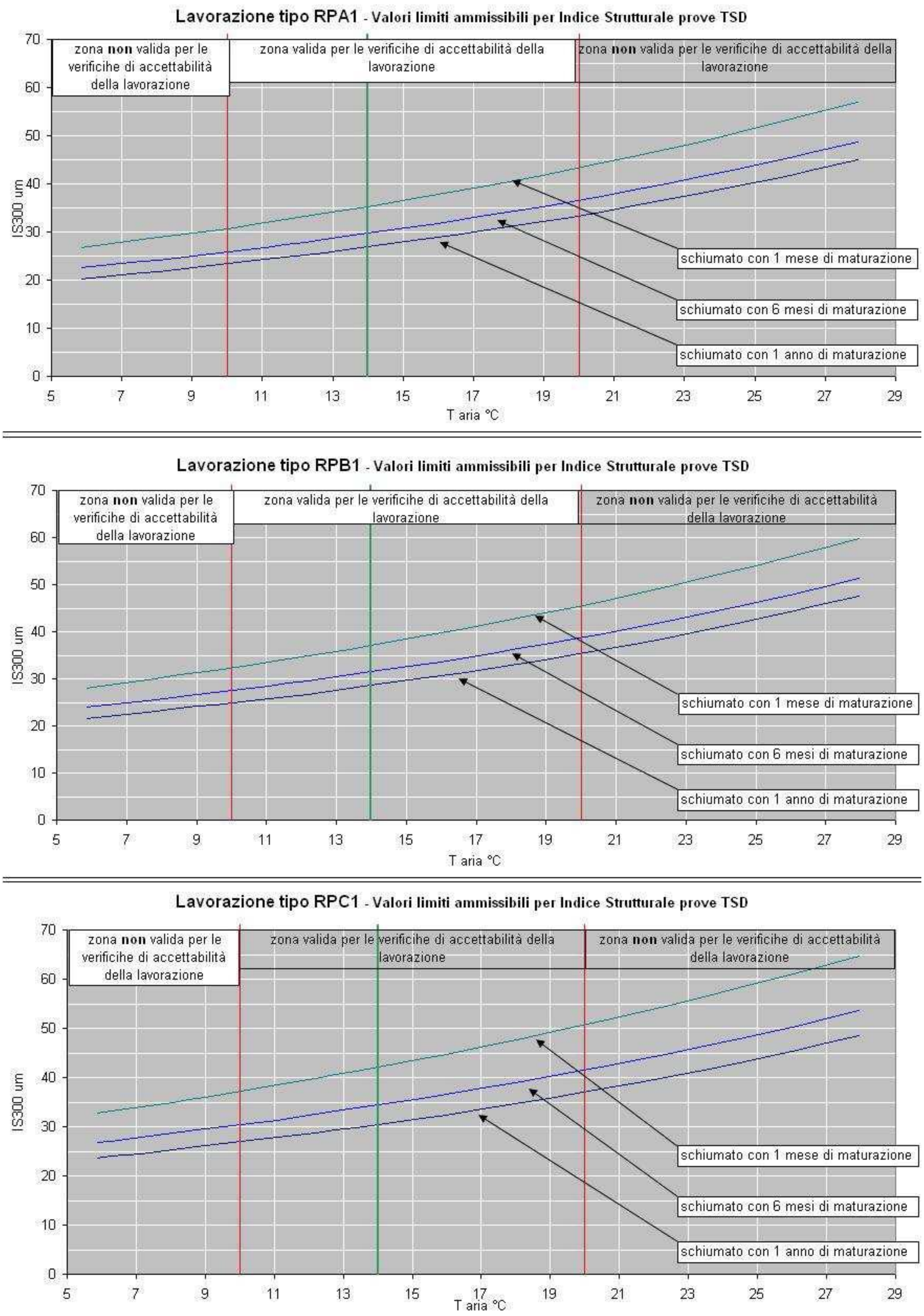

Figure 3 – 9 Example of graphs in Anas technical standards

The test conditions are evaluated through the actual temperature of the air at the time of the test. The tests are usually performed at a given reference temperature air (14°C), but in any case can be considered valid if they are contained in the intervals of air temperature between 10 and 20°C as shown in the figure 3-9.
The correction factor, by which to multiply the values of SCI300 is provided by the following expression:

$$\frac{SCI_{14°C}}{SCI_{Ttest}} = exp \cdot (C \cdot 14 - T_{test})$$

$SCI_{14°C}$ the value of SCI300 normalized at 14°C
SCI_{Ttest} the value of SCI300 during the test
T_{test} test temperature air
C = 0.037 in case of RP or NC otherwise = 0.022 for RS

3.4.2 Vehicle speed

Early testing by TRL showed that although the UK TSD gave comparable results at different speeds (60, 70 and 80 km/h) the rate at which acceptable data was collected decreased significantly at higher speeds leading to excessive noise in the processed results. Similar issues were reported by DRD using the DK TSD. By modifying the equipment and mounting the beam holding the lasers directly to the vehicle chassis the problem was solved and the UK TSD now operates satisfactory up to 80 km/h. Subsequent investigation by TRL showed a relationship between deflection slope and the speed of the vehicle for different types of pavement bases. The trend seemed to be a reduction of deflection slope with the vehicle speed but was very modest to take in account (figure 3-10).

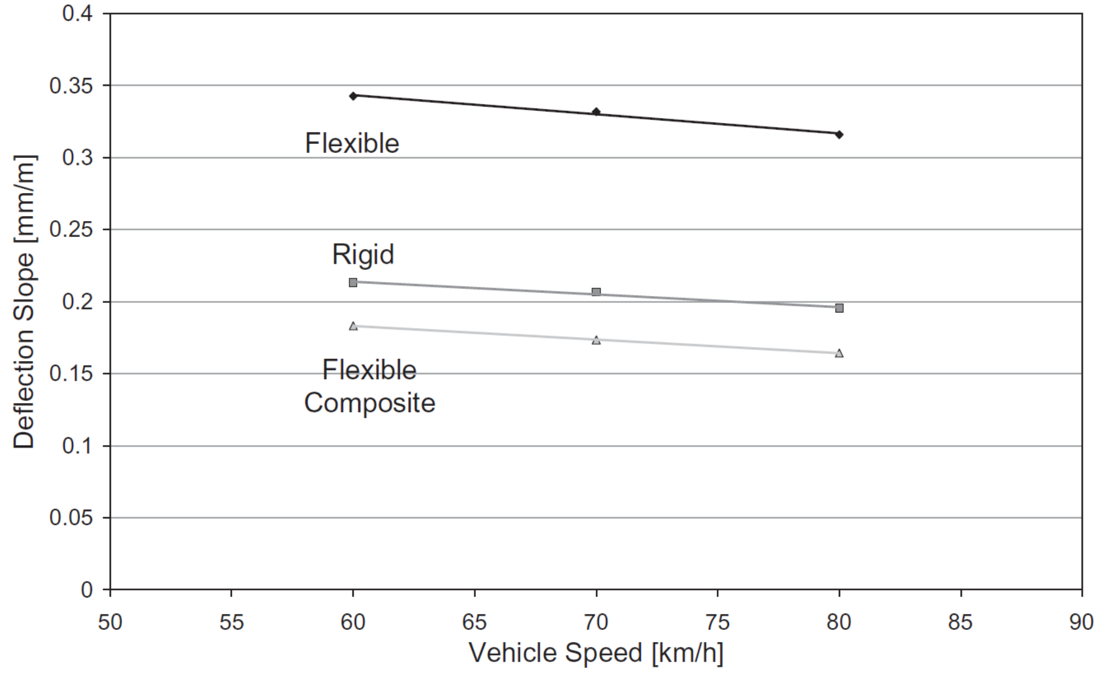

Figure 3 - 10 Effect of vehicle testing speed on deflection slope

In 2011 RTA made some tests at different survey speeds: 40 km/h, 60 km/h and 80 km/h. The testing at the trial sites didn't appear to demonstrate a speed dependency for the TSD (figure 3-11).

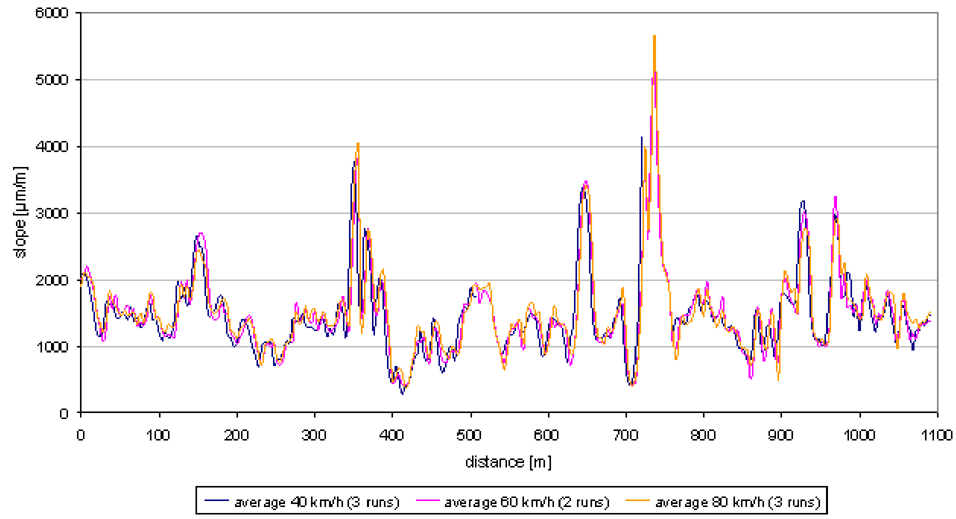

Figure 3 – 11 TSD slope values measured at 40, 60 and 80 Km/h at Oolong

The same result came from a research of Dr. Jorgen Krarup by Greenwood Engineering in Denmark in 2011. The TSD reproduced similar outputs on a test section when measuring at different driving speed (figures 3-12 and 3-13).

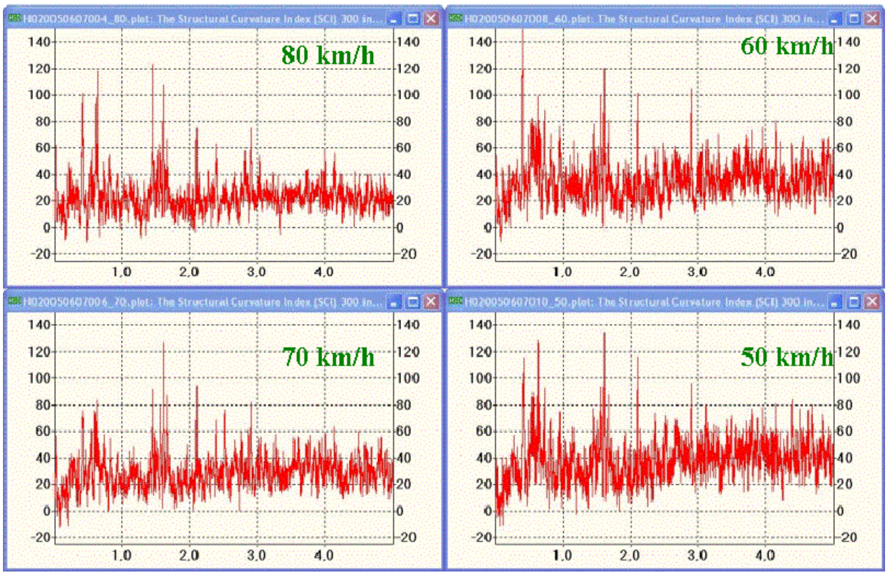

Figure 3 – 12 SCI300 from 5 Km rigid pavement measured at 50, 60, 70 and 80 Km/h

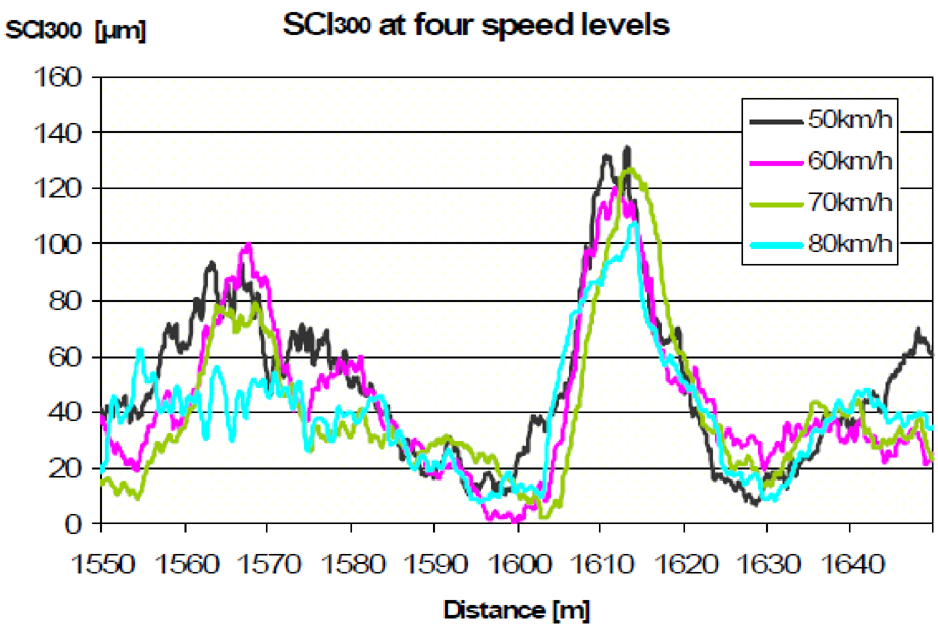

Figure 3 – 13 Zoom of 100 m from figure 3-12

3.4.3 Pavement differentiation (strong vs. weak)

As would be expected, previous evaluations of TSD type devices have included assessment of their ability to differentiate between strong and weak pavements, and pavement type (Baltzer & Hildebrand 2007, Ferne et al. 2009b, Krarup et al. 2006, Rasmussen & Hildebrand 2002, Rasmussen, Krarup & Hildebrand 2002, Simonin et al. 2005). Some studies indicate that the TSD is able to differentiate between different asphalt pavement types or pavement design classes (Baltzer & Hildebrand 2007)[14]. As shown in figure 3-10, UK studies (Ferne et al. 2009a) have shown that the TSD produces noticeably different deflection slope readings for flexible, rigid and flexible composite pavements. Baltzer & Hildebrand (2007) suggests the TSD will be especially well suited for scanning the bearing capacity of large road networks for which there is limited or no information known about the structural pavement condition.

Along with evaluating the TSD capability in pavement deflection testing, researchers have been investigating the relationship between the TSD and other pavement deflection testing devices such as FWDs and deflectographs (DFGs). The results indicate a relationship between these devices on the individual pavements tested. Roberts and Byrne (2008)[15] note that there is agreement between the results from each device and the overall trend for the pavement strength profile. The specific relationship between deflections measured with the different devices, however, varies with the specific pavements tested. Researchers involved in these studies agree that with further testing and analysis a generally applicable relationship could be defined.

Comparison testing has involved direct comparison of slope (TSD) to deflection (FWD and deflectograph), comparison of SCI300 (TSD) to SCI300 (FWD) etc.

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14 Baltzer, S., Hildebrand, G., 2007. "HSD measurements at the BASt test track- COST 354: short term scientific mission". Hedehusene, Denmark.

15 Roberts, J., Byrne, M., 2008. "An initial review of Greenwood traffic speed deflectometer (TSD) and its potential applicability for the RTA". Contract report, ARRB Group, Vermont South, Vic.

Figure 3-14 is an example of the graphical presentation of results that shows the potential of the TSD.

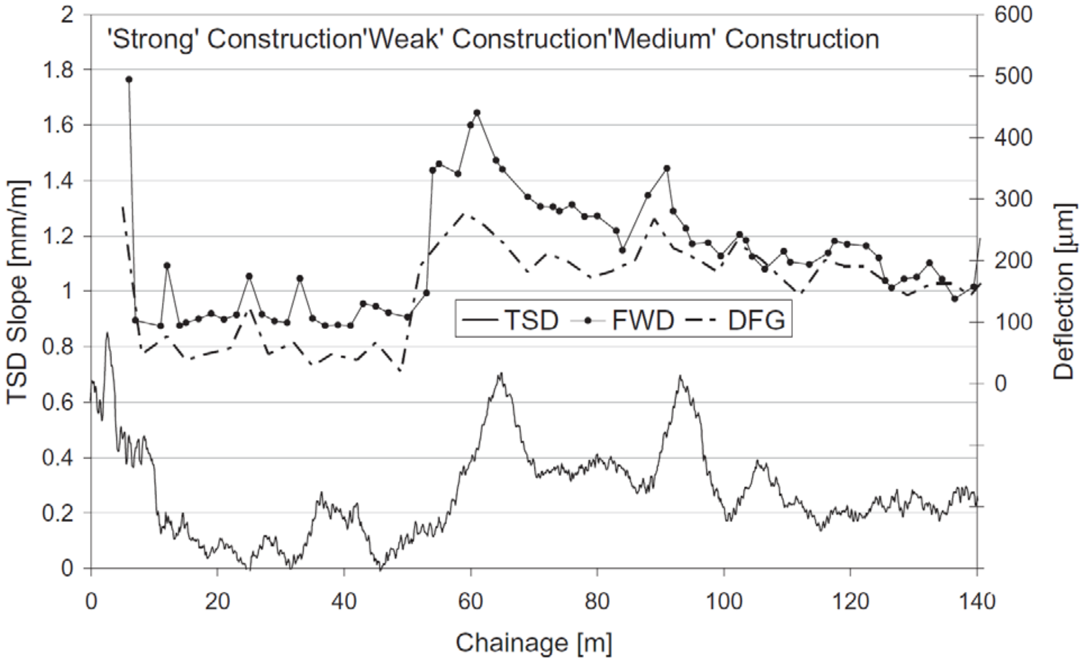

Figure 3 – 14 TRL TSD deflection slope, FWD and Deflectograph central deflection

Results indicate it is possible to define a direct relationship between deflection-measuring devices that would allow TSD data to be converted into equivalent FWD/DFG data. TRL has planned to relate the value of the TSD deflection slope to absolute deflection (maximum deflection D0) as measured by the deflectograph. In fact results clearly show that the TSD and deflectograph measurements are related but TRL hasn't published the relationship yet (Jenkins 2009)[16].

In the longer-term both TRL and DRD are hoping to use direct TSD data for determining the structural capacity of road networks and for input into forward planning (Baltzer 2009 and Jenkins 2009). This, of course, will require extensive

16 Jenkins, M., 2009. "Geometric and absolute calibration of the English Highways Agency traffic speed deflectometer". Young researchers seminar, Torino, Italy, European Conference of Transport Research Institutes (ECTRI), Bron, France.

long-term data on the actual performance of road pavements in their respective networks.

3.4.4 Road surface characteristics

Some works have been undertaken looking at the influence of road surface characteristics on the performance of the TSD in terms of data quality. Surface color, wetness, macro-texture and roughness have been considered.

TRL determined that the performance of the UK TSD laser optical system is influenced by the road surface. It has determined the system performs better on light color surfaces (such as concrete) and least well on new bituminous, presumably asphalt, surfaces (Ferne et al. 2009a). Similarly, damp roads yield a lower data rate than dry surfaces.

Ferne et al. (2009a) note that TRL considers this phenomenon is related to the optical properties of the different surfaces or surface condition, but is yet to fully understand the cause and effect. TRL recognizes that further work is required to define the capabilities of the technology in relation to various surface characteristics.

DRD undertook a short survey on some local rural roads to look at the influence of macro-texture (including a small aggregate sprayed seal) on the quality of DK TSD data. Unfortunately, testing conditions were less than ideal, with the road being damp during testing, the ambient temperature at close to the lower operational limit for the lasers, and the geometry of the road prohibiting high collection speeds. DRD informed that no impact on data quality could be discerned, however, further testing on the surface characteristic were needed to be conclusive (Roberts & Byrne 2008).

In the same study on macro-texture DRD looked at the effect of roughness. DRD found phase noise and vibration increases with increasing speed on rough roads. It concluded that the DK TSD would operate effectively up to 65 km/h (the maximum speed achieved during the study due to road geometry and speed limits) on the rough test roads without problems (Roberts & Byrne 2008).

In 2011 RTA advised that pavement roughness has the potential to affect TSD's measurements of deflection response in two ways: by affecting the instantaneous loading of the pavement and the optical system of Doppler laser.

Separate research by TRL and DRD has shown that a poor longitudinal profile is associated with poor data quality (low data rate). A review of deflection data and roughness condition (separately measured on different days) indicates a relationship, shown in figure 3-15, with distinct peaks of relative high roughness (expressed by the IRI value) accompanied by distinct peaks of high TSD slope values.

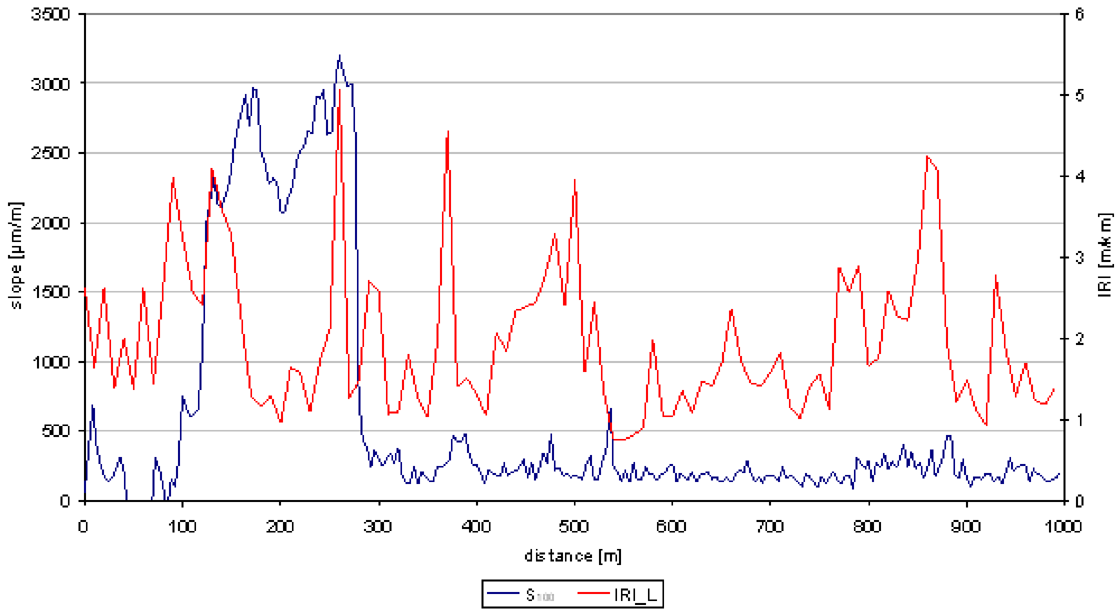

Figure 3 – 15 Comparison of TSD slope measured at 60 Km/h and roughness IRI (10 m running average) at Illawara

Roughness is commonly associated with weak and deformed pavements so it is possible an increase in slope associated with high roughness could be associated with a weaker pavement. Other devices (FWD and DFG) showed similar deflection peaks as the TSD slope measurements so it is possible to conclude the pavement is weak and rough at those locations. The concern is the true slope measure may be masked by the combined influence of roughness and the dynamic load.

According to the test notes of the TSD crew, the measurements at one test site were particularly influenced by the varying and bumpy surface and it is noted that the uneven surface resulted in the Doppler laser losing its focus.

Baltzer et al. (2010)[17] conclude that bumpy rides (i.e. roughness) will influence results and suggest this is predominantly due to dynamic loading effects as the load applied by the TSD varies from the stationary axle load.

Further investigations on the influence of roughness on deflections pavements are necessary and this is the object of this thesis.

3.4.5 TSD measurements

RTA (Roads and Traffic Authority) in Australia has provided measures of TSD SCI300, TSD D0 and slope for P100, P200 and P300 for each TSD survey. As mentioned TSD SCI300 and TSD D0 are modeled indicators of SCI300 and D0 rather than a traditional measurement of a direct pavement response. Figure 3-16 shows all indicators have similar response profiles and the figure 3-17 illustrates the results from the different lasers. P100, P200 show little variation suggesting some similarity as an indicator of pavement response that should be further explored. The P300 laser does not seem to follow the deflection profile as closely.

[17] Baltzer, S., Pratt, D., Weligamage, J., Adamsen, J., Hildebrand, G., 2010. "Continuous bearing capacity profile of 18 000 km Australian road network in five months". ARRB conference 24th, Melbourne, Victoria, Australia.

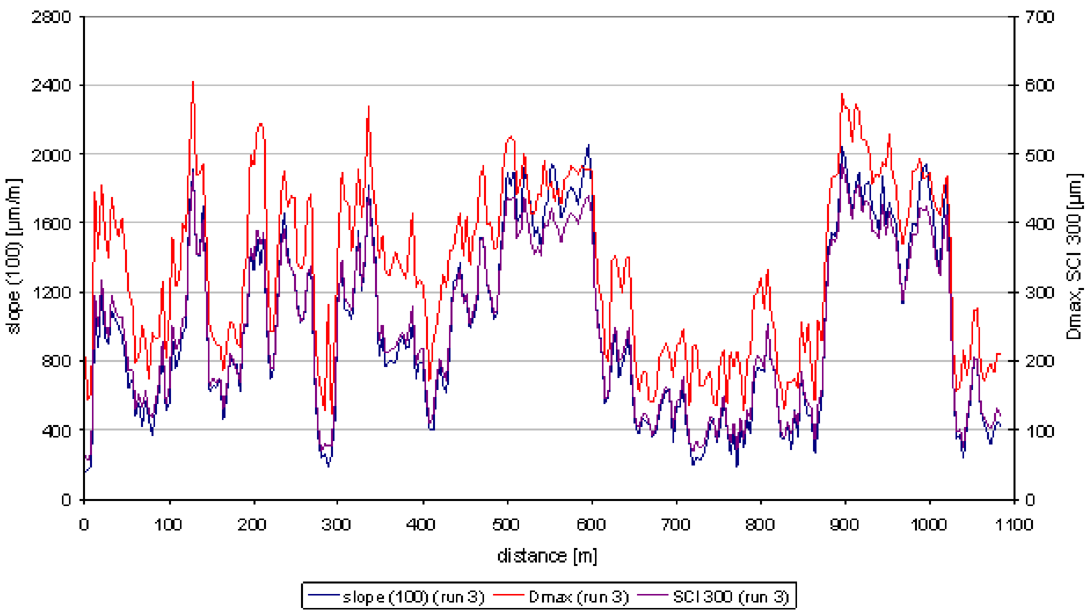

Figure 3 – 16 TSD slope, TSD Dmax and TSD SCI300 measure at 60 Km/h at Illawarra

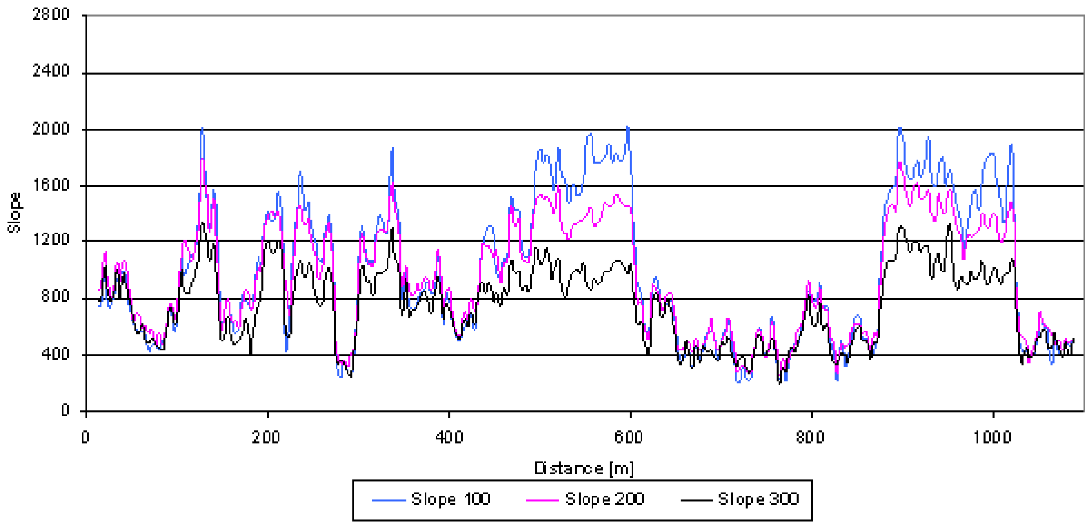

Figure 3 – 17 TSD slope S100, S200 and S300 at 60 Km/h at Illawarra

3.5 Recording and reporting intervals

3.5.1 Information quality level (IQL)

The concept of information quality level (IQL) as developed by the World Bank (Paterson & Scullion 1990 and Bennett & Paterson 2000, and described in

Austroads 2009a)[18]. This is a means of classifying data appropriateness in terms of detail, and hence the appropriate reporting length.

IQL levels within the context of asset management data and the TSD are presented in table. Figure 3-18 illustrates the overall IQL concept that links data detail requirements to the decision-making purposes the data serves.

IQL	Data description	Current examples	TSD equivalent
1	Data is used for research, laboratory or theoretical investigations. It includes detailed data mostly collected electronically at high frequency.	Raw data files of high speed roughness (IRI) and rutting data.	Machine and raw data directly sourced from TSD for window at minimum increment.
2	Data is used for engineering analysis and project level works.	Outputs associated with Austroads test methods i.e. 20-100 m IRI and rutting data, project level FWD results.	Processed/recorded data. Test method output (method, output and length still to be defined).
3	Data is most appropriate for network level analysis and planning. The number of attributes is reduced to a select few and aggregated parameters are used. Data collected with less sophisticated methods or computed from lower level data (rating also falls into this category).	100 m IRI data considered at the link level i.e. average IRI, % and location of IRI failures on the link. Rated condition data obtained from video data.	Processed/reporting data. Suitable for asset management decision making and input into PMS.
4	Includes a select few summary data items that are used mainly for senior management reports requiring relatively low level technical expertise. Data is collected with low cost manual or visual methods or computed from lower level data.	Consolidated pavement condition indicators. Safety star rating of links.	Processed/reporting data. Suitable for monitoring performance.
5	Data is mostly used to communicate network level information in simple, mostly nontechnical terms. Key performance indicators and other composite indexes fall into this category.	% of network meeting smooth ride targets (IRI standards).	Network level reports e.g. % network > x deflection.

Table 3 - 1 IQL definitions

18 Paterson, Scullion, T., 1990. “Information systems for road management: draft guidelines on system design and data issues”. Technical paper INU77, Infrastructure and Urban Development Department, World Bank, Washington, DC, USA.

Bennett, C., Paterson, 2000. “A guide to calibration and adaptation of HDM-4, highway development and management series”. Vol. 5 World Roads Association, PIARC, Paris, France.

Austroads, 2009a. “Guide to asset management: part 5A: inventory”. Sydney, NSW

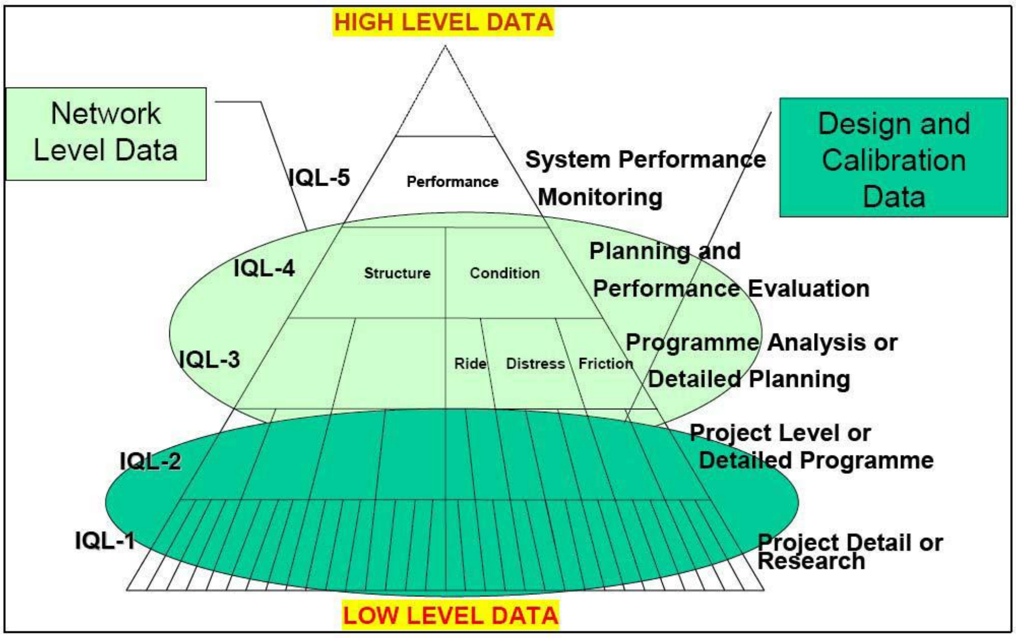

Figure 3 – 18 Information quality level

The TSD collects data at a fine resolution and in its raw form (measurements every 20 mm) is considered to provide a lot of data at too fine a resolution for most decision-making purposes. As with other high-speed devices, aggregating data to an appropriate reporting length is an acceptable solution. At the May 2010 working group meeting it was agreed the TSD data analysis would focus on data required for asset management purposes; this relates to IQL-3. For example 100 m roughness is a common length used by asset managers as well as project staff.

To assist in defining and determining an appropriate reporting length, the following guiding principles have been defined:

- a reduction in the total volume of data to reduce storage space requirements
- independence of aggregation direction (test method)

- the level to which classification and differentiation of different pavement sections can be based on an appropriate TSD output (S300 was used for this investigation)
- the ability to integrate the processed data with pavement management systems
- the level to which local peaks (which are possible indicators of weak sections of pavement) can be identified and located
- contribution of data to asset management decision making.

3.5.2 Raw and machine data

TSD data at IQL-1 is shown in figure 3-19. It is accepted that this IQL is too detailed for most asset management decision making and some form of smoothing as shown in the next figure would be beneficial.

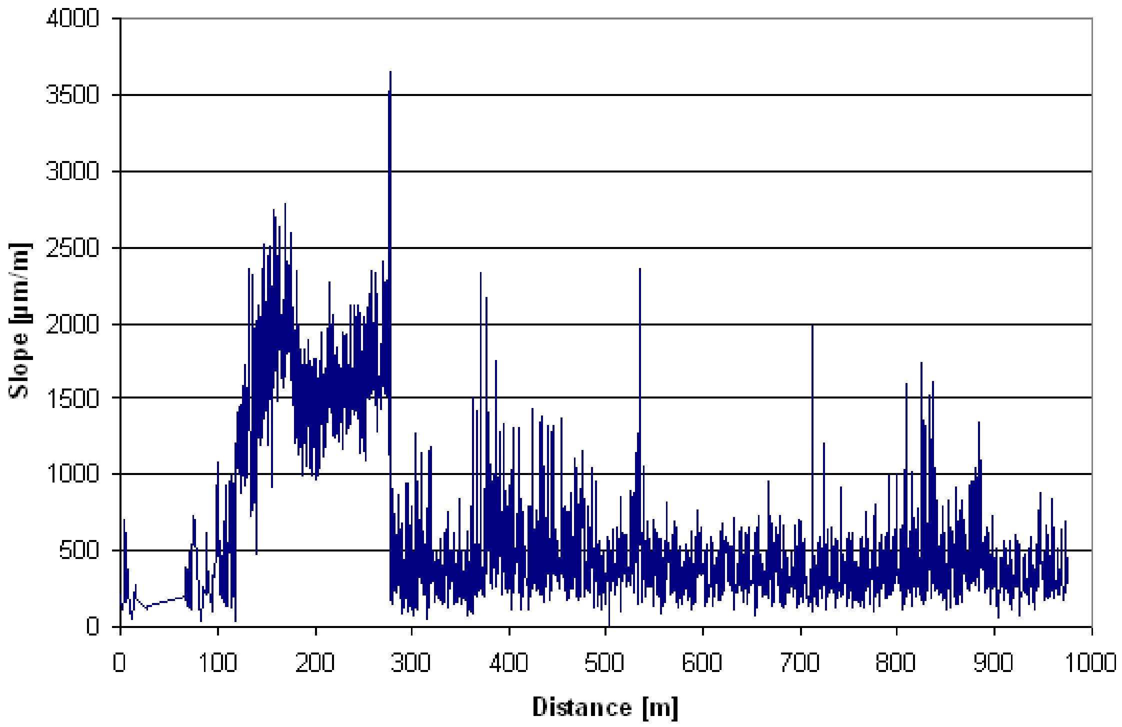

Figure 3 – 19 Raw slope data for Illawarra

The smoothing shown in figure 3-20 was achieved by adding a moving average trend line. Some of the peaks in the data are lost. These could be sections of weak pavements, so there needs to be a logical and systematic method to using smoothing techniques and averaging the data for reporting.

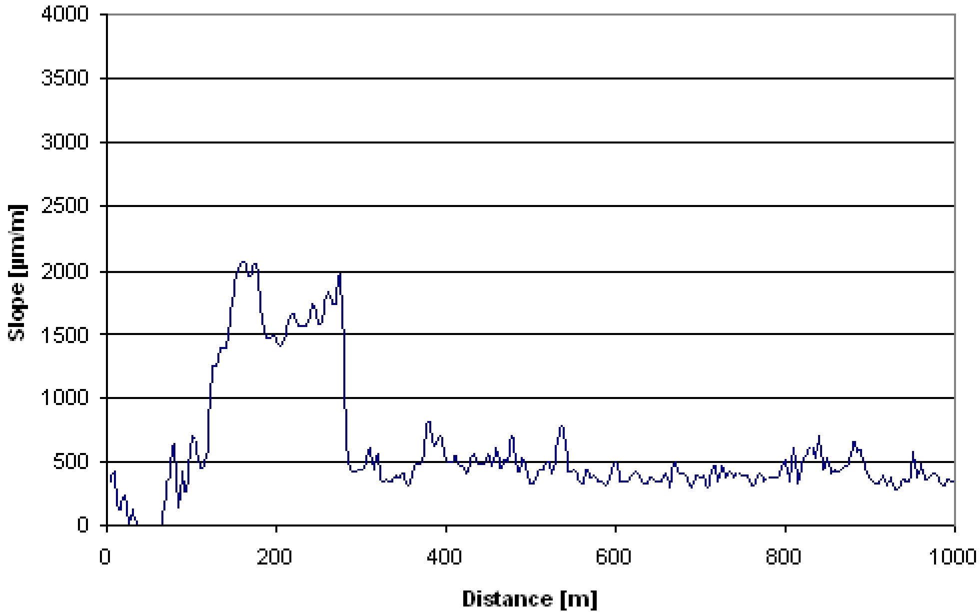

Figure 3 - 20 Smoothed raw slope data for Illawarra

Nevertheless whilst the TSD is in its early days of evolution it is recommended that as with profilometer data the TSD raw and/or machine data be archived for quality control and research purposes, on the assumption the data can be reprocessed for a specific purpose at a later date.

The amount of storage space required to store data at this level is a consideration, with one kilometer taking approximately 6 megabytes of disk space. While this may seem considerable the cost of hard disks capable of storing this amount of data is negligible (e.g. a 1 Terabyte hard disk will be sufficient for > 170 000 km of TSD data).

3.5.3 Simple aggregation method

This method involves averaging the TSD outputs over a set reporting length and is the same method currently used by TRL. The deviation of results from the mean has also been considered in this analysis as an indicator of the variance within each reporting length and the maximum deflection (i.e. S300) as a worst case indicator.

3.5.4 One meter reporting length

One meter is considered the minimum practical length for reporting as a shorter length will provide an inadequate reduction of volume over the raw data. One meter data could possibly be used for research and other IQL-1 purposes. TRL have recently advised that 1 m is now their base reporting length for surveys as whilst the data still contains some noise, a longer length (and an increased averaging/smoothing of data points) risks losing information useful for some applications.

With large surveys the 1 m reporting length may not provide a significant reduction in data volume to make it feasible to integrate with existing databases and pavement management systems. No other parameters are reported at a 1 m interval for asset management IQL-3 purposes. The 1 m reporting length has the lowest standard deviation of all the reporting lengths investigated. This is most likely due to a 1 m reporting length having the lowest number of data points to be aggregated. Figure 3-21 shows the 1 m reporting length for Illawarra site in Australia.

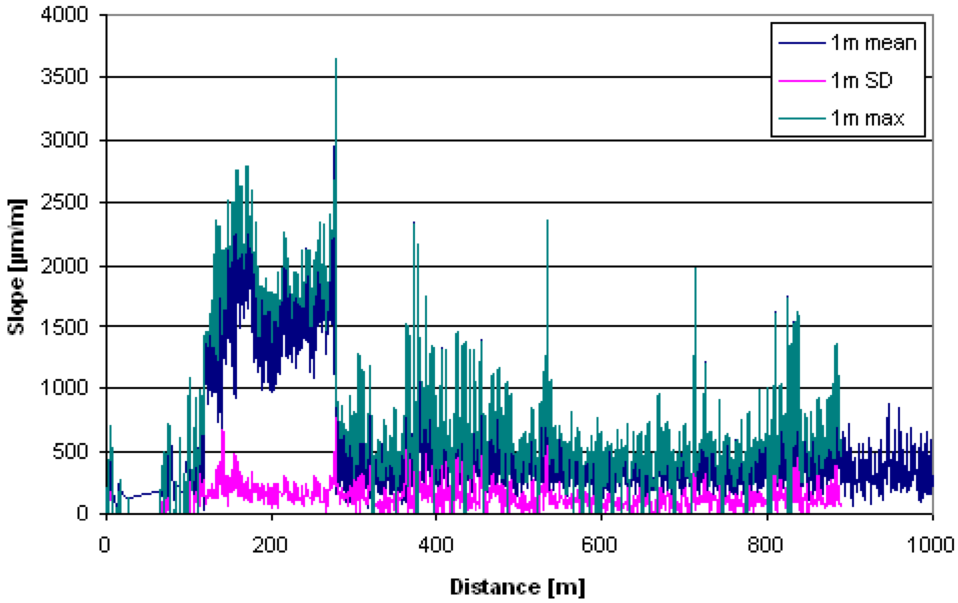

Figure 3 – 21 One meter reporting lenght for Illawarra

3.5.5 Five to 20 m reporting length

A reporting length of 5 through to 20 m is considered a reasonable compromise between data volume and resolution. In terms of IQL, reporting lengths of 5 to 20 m would be considered IQL-2, meaning data at this length interval could be used for either research or project-level analysis. While the TSD data could theoretically be used for project-level analysis, this report does not investigate the appropriateness of using the TSD. Figure shows the 5 and 20 m reporting length analysis for Illawarra site. The figure 3-22 illustrates that at 20 m most deflection peaks and the general profile of TSD responses remain; although peaks shown in the 5 m and 1 m data are smoothed out (i.e. between 820 and 840 chainage).

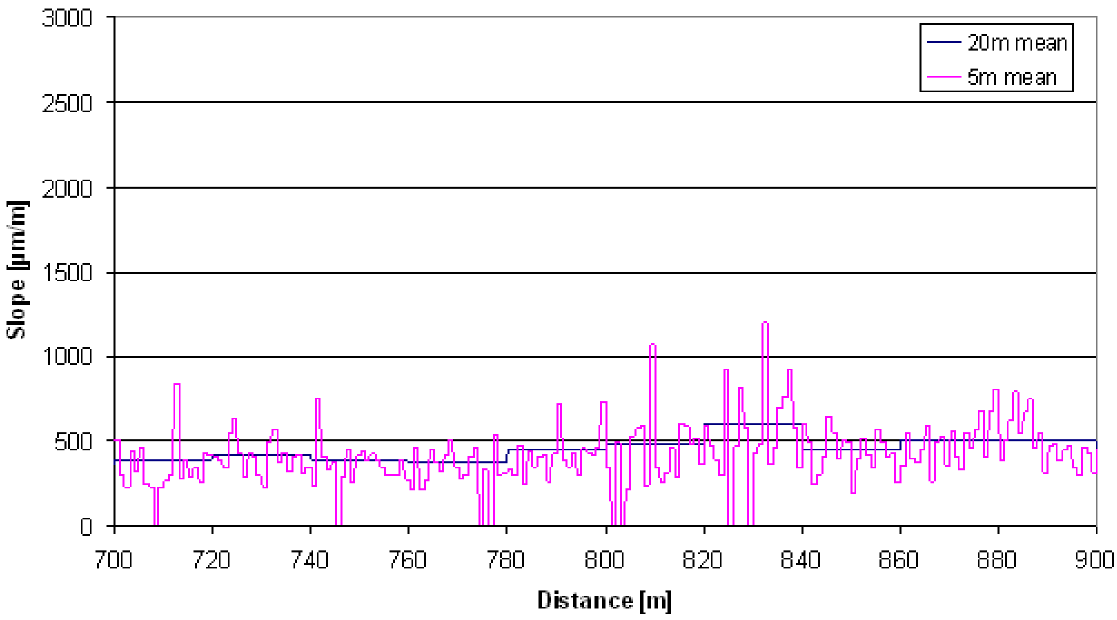

Figure 3 – 22 Five meter and 20 m reporting length for Illawarra

3.5.6 Fifty to 100m reporting length

A reporting interval of 50 to 100 m is considered equivalent to IQL-3 and suitable for network level asset management. Additionally, data at this interval should easily be incorporated into an existing assets register and asset databases given that other condition data is already reported at these intervals. The analysis shows data presented at a 50 m interval enables the asset manager to see the severity and range of pavement condition (illustrated in figure 3-23). The disadvantage is that at reporting intervals greater than 50 m, important variations in deflection may be masked i.e. the data is smoothed such that it loses its fidelity. Figure 3-24 presents data at a 100 m reporting interval.

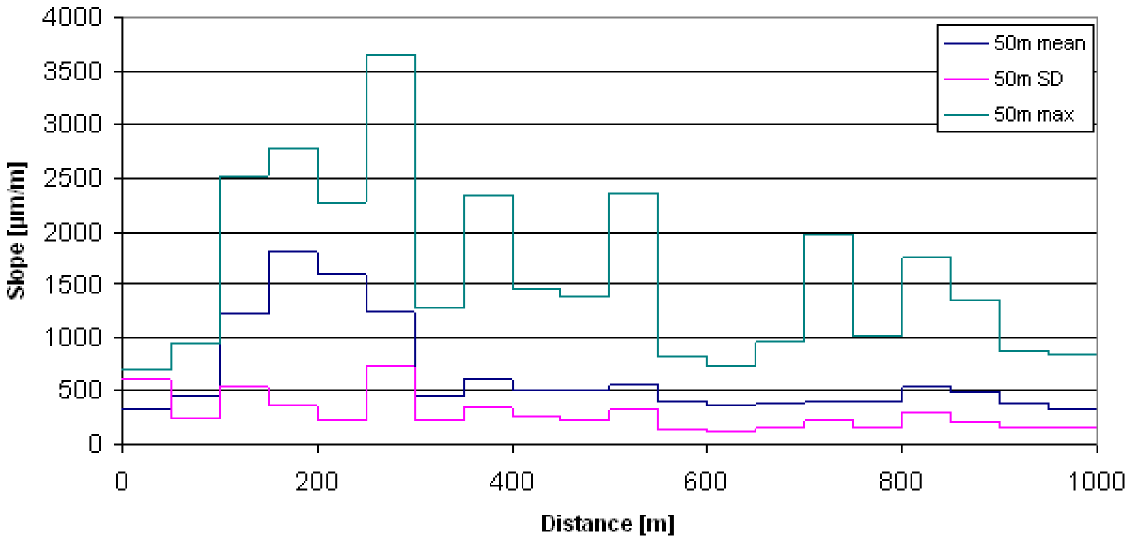

Figure 3 – 23 50 m reporting length for Illawarra

Another characteristic with using a larger reporting interval is that sections with a low data rate (i.e. poorer data quality) could be obscured. As mentioned previously TRL has observed a drop in data rate corresponding to low deflection readings. It is possible this could lead to lower deflection results for some reporting lengths. However, it is anticipated that developments in raw data processing could remove this potential bias.

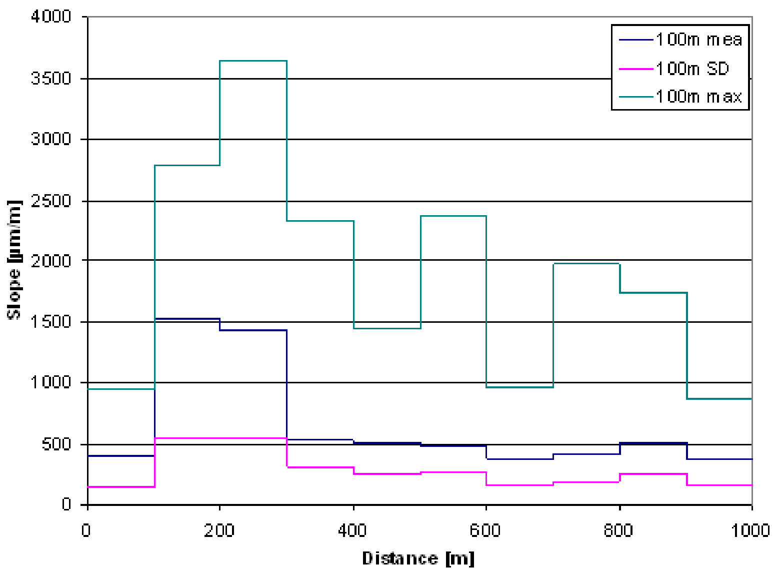

Figure 3 – 24 100 m reporting length for Illawarra

Chapter 4
RESEARCH AND DATA ANALYSIS

4.1 Introduction

ANAS S.p.A. manages and maintains the main Italian roads. The overall extension currently is about 25000 km, including the network in granting 6000 km to the motorway companies, in relation to which ANAS S.p.A. plays the role of control and surveillance. The management of an infrastructure network such extensive and articulated poses serious and complex problems, especially in the vital area of the conservation of pavements. The problem of the evaluation of state has been successfully faced for the surface characteristics, for which already exist and are operational high-efficiency devices used for diagnostic status and acceptance of the work. On the other hand, until recently the most common use for the bearing capacity was of slow devices, which normally needed to stop or proceed at low speed.

With the use of the Traffic Speed Deflectometer the final measure of the bearing capacity by the value of SCI "summarizes" all the actions and performs quickly and at low cost a control on the overall result of work, so the effective performance of all realized. Thus it appears to be an ideal tool for the acceptance of the work and also for the management of a maintenance program at network level for a national agency such as ANAS.

Like all the new devices, it reported an initial distrust or even a real opposition from various parties involved in the construction of roads. It is necessary to demonstrate the reliability of this tool in relation with the measuring devices which are now used and commonly accepted.

However we can find TSD in the new performance specifications of ANAS as a tool of control and acceptance. Therefore it is necessary to have full knowledge of the factors that affect the measurement of bearing capacity because the ANAS's specifications impose a reduction of the contract price equal to half of the percentage points by which the structural index differs from the prescribed limit value. From the studies conducted the three main factors that affect the measurement of bearing capacity of the pavement by TSD are: temperature, frequency of load application and the roughness of the surface. As reported in Chapter 3 ANAS has already conducted its own tests to assess the influence of the temperature calibrating a relation that standardize the value of SCI at 14°C of the air. Also for the frequency of load application which is a direct function of the vehicle speed, ANAS adopts the results of RTA in Australia: for speeds between 40 Km/h and 80 Km/h, the frequency does not affect the bearing capacity. For the roughness of the surface until now have only been performed qualitative studies. One of the targets of this thesis is to evaluate in a proper way the influence of this factor on the TSD's measurements of bearing capacity to improve the reliability if it's possible.

In the last part of the research we have evaluated the influence of temperature on the value of bearing capacity and unlike what ANAS has been doing at the date, we take in account the temperature of the pavement as well as the temperature of the air.

4.2 Set of data

The research is carried out on a set of data that has been provided by ANAS on a section of the bypass road of Bari using the Traffic Speed Deflectometer and the Falling Weight Deflectometer. In fact, the reliability of TSD is evaluated basing on the results obtained by the FWD which is the commonly accepted device. The choice of FWD's configuration was that it worked at a pressure of 850 kPa equal to the inflation of the wheels of the TSD so we obtained comparable results after correction with the temperature.

The data are referred to a section of road of about 20 km with an interval between TSD's data of 10 m while the average interval for FWD is 50 m.

Different is also the period of registration of the results because the TSD was used in July while the FWD was used in October so either air and pavement temperatures were markedly different.

4.3 Data analysis

The enormous amount of data available has required the creation of a software in PHP language that would manage them and would make correlations automatically according to certain parameters settings (Appendix A).

The reliability of the TSD is evaluated by three statistical parameters: root mean square deviation (RMSD), percentage root mean square deviation (%RMSD) and mean absolute percentage error (MAPE)

4.3.1 Root mean square deviation (RMSD) and Percentage root mean square deviation (%RMSD)

RMSD and %RMSD are frequently used measures of the differences between values predicted by a model or an estimator and the values actually observed. Basically, the RMSD (and %RMSD) represents the sample standard deviation (and percentage standard deviation) of the differences between predicted values and observed values. RMSD and %RMSD are good measures of accuracy, but only to compare forecasting errors of different models for a particular variable. They are measures of dispersion.

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \langle x_i \rangle)^2}{N}}$$

$$\%RMSD = \sqrt{\frac{\sum_{i=1}^{N}(\frac{x_i - \langle x_i \rangle}{\langle x_i \rangle})^2}{N}} \cdot 100$$

Where:

$$\langle x_i \rangle = the\ true\ value$$
$$x_i = the\ estimation\ value$$

A low RMSD or %RMSD indicates that the data points tend to be very close to the mean (also called expected value), instead a high value indicates that the data points are spread out over a large range of values.

4.3.2 Mean absolute percentage error (MAPE)

The mean absolute percentage error (MAPE), also known as mean absolute percentage deviation (MAPD), is a measure of accuracy of a device in a statistics way. It usually expresses accuracy as a percentage, and is defined by the formula:

$$MAPE = \frac{1}{N} \cdot \sum_{i=1}^{N} \left| \frac{x_i - \langle x_i \rangle}{\langle x_i \rangle} \right| \cdot 100$$

Therefore the MAPE is the average error that we can associate with the measure by TSD.

4.3.3 First results

Figures 4-1 and 4-2 produced by the software report in the ordinate the values of SCI300 standardized at 14°C of the air by the two devices and in the abscissa the chainage, for the left and right roadway.

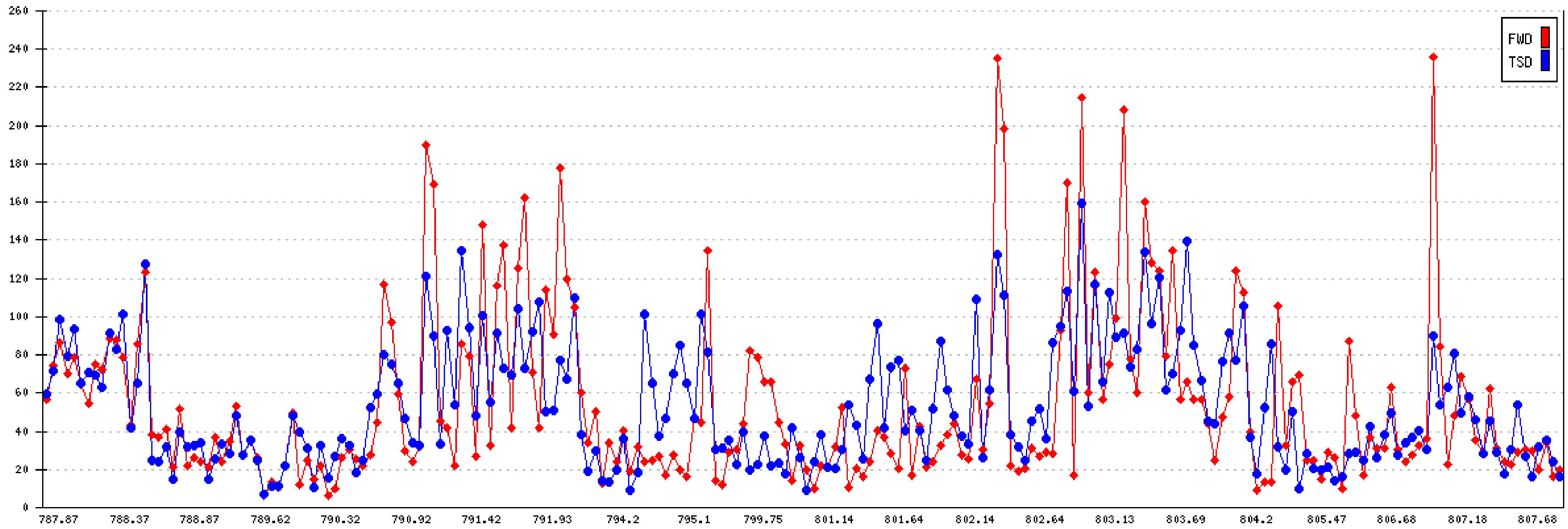

Figure 4 - 1 Left Roadway

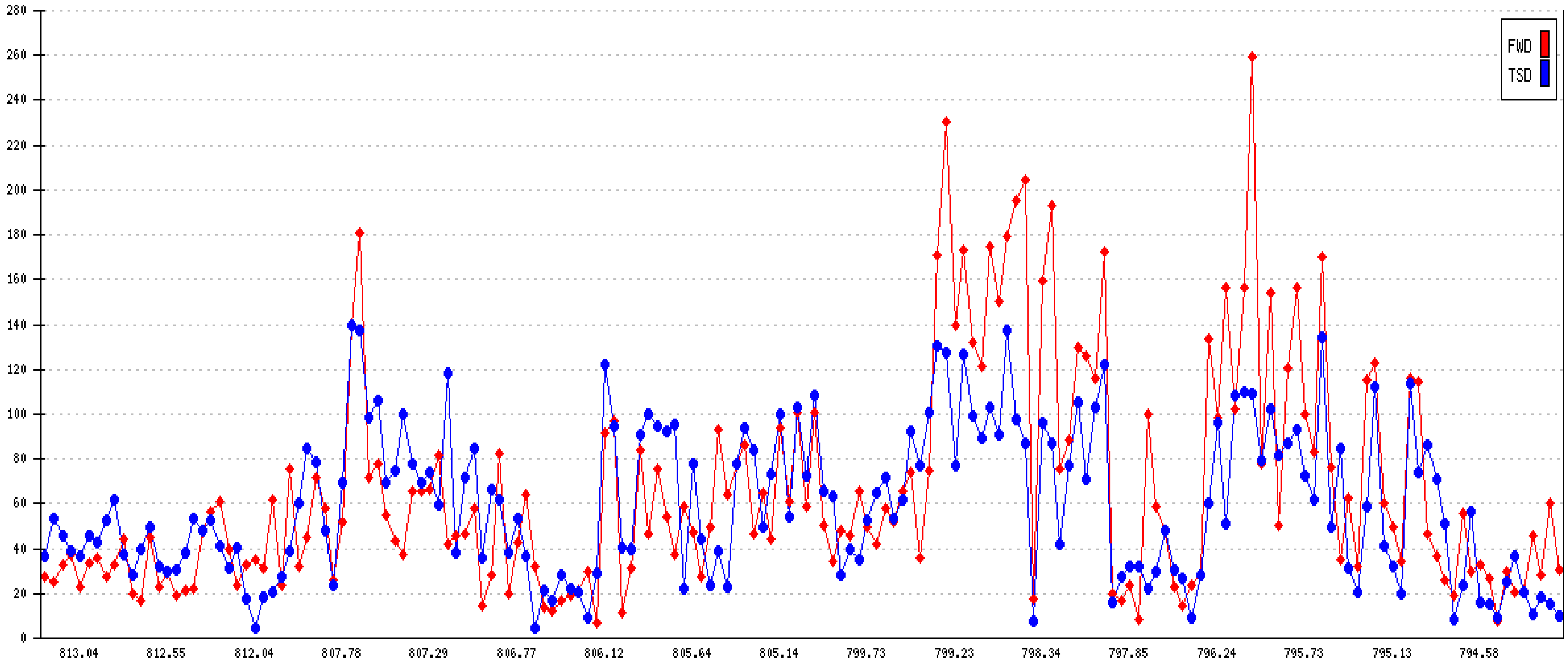

Figure 4 - 2 Right Roadway

From a pure qualitative analysis we can realize the way the TSD gives values of SCI300 at 14°C lower than the FWD when it measures values higher than 140 μm and the Traffic Speed Deflectometer produces a smoother oscillation of the parameter.

As stated by ANAS we get a satisfactory correlation between the two tools for use at network level (not for project level) and the following table shows the results obtained in terms of RMSD, %RMSD and MAPE for the two roadways.

	Left Roadway	**Right Roadway**
RMSD(μm)	33.19	35.41
%RMSD	93.03%	68.59%
MAPE	57.08%	49.40%

In the next paragraphs we will try to achieve a higher level of reliability of measurements of bearing capacity by TSD through assessments on roughness of the surface and temperature of pavement.

4.4 Effects of the roughness of the pavement

The roughness of the pavement affects the measure of bearing capacity by Traffic Speed Deflectometer according two ways. The first one affects the optical system of measurement because an excessive dispersion of the reflected rays gives a poor reliability of the acquired data, the second one produces an increase of the dynamic load on the pavement.

The FWD is not subject to this factor so for this reason is an ideal tool for comparison.

We have chosen IRI (International Roughness Index) as an identification parameter of this feature because the TSD measures it continuously and mediating it over a length of 10 m.

4.4.1 International Roughness Index (IRI)

The International Roughness Index (IRI) is the roughness index most commonly obtained from measured longitudinal road profiles. It is calculated using a quarter-car vehicle math model, whose response is accumulated to yield a roughness index with units of slope (in/mi, m/km, etc.). Since its introduction in 1986, IRI has become the road roughness index most commonly used worldwide for evaluating and managing road systems.

In the early 1980 the highway engineering community identified road roughness as the primary indicator of the utility of a highway network to road users.

their However, existing methods used to characterize roughness were not reproducible by different agencies using different measuring equipment and methods. Even with a given agency, the methods were not necessarily repeatable. Nor were they stable with time.

The United States National Cooperative Highway Research Program (NCHRP) initiated a research project to help state agencies improve use of roughness measuring equipment. The work was continued by The World Bank to determine how to compare or convert data obtained from different countries (mostly developing countries) involved in World Bank projects. Findings from the World Bank testing showed that most equipment in use could produce useful roughness measures on a single scale if methods were standardized. The roughness scale that was defined and tested was eventually named the International Roughness Index.

The IRI was defined as a mathematical property of a two-dimensional road profile (a longitudinal slice of the road showing elevation as it varies with longitudinal distance along a travelled track on the road). As such, it can be calculated from profiles obtained with any valid measurement method, ranging from static rod and level surveying equipment to high-speed inertial profiling systems.

The quarter-car math model replicates roughness measurements that were in use by highway agencies in the 1970s and 1980s. The IRI is statistically equivalent to the methods that were in use, in the sense that correlation of IRI with a typical instrumented vehicle (called a “response type road roughness measuring system” RTRRMS) was as good as the correlation between the measures from any two RTRRMS's. As a profile-based statistic, the IRI had the advantage of being repeatable, reproducible, and stable with time. The IRI is based on the concept of a “golden car” whose suspension properties are known. The IRI is calculated by simulating the response of this “golden car” to the road profile. In the simulation, the simulated vehicle speed is 80 km/h. The properties of the “golden car” were selected in earlier research to provide high correlation with the ride response of a wide range of automobiles that might be instrumented to measure a slope statistic (m/km). The damping in the IRI is higher than most vehicles, to prevent the math model from “tuning in” to specific wavelengths and producing a sensitivity not shared by the vehicle population at large.

The slope statistic of the IRI was chosen for backward compatibility with roughness measures in use. It is the average absolute (rectified) relative velocity of the suspension, divided by vehicle speed to convert from rate (e.g. m/s) to slope (m/km). The frequency content of the suspension movement rate is similar to the frequency content of chassis vertical acceleration and also tire/road vertical loading. Thus, IRI is highly correlated to the overall ride vibration level and to the overall pavement loading vibration level. Although it is not optimized to match any particular vehicle with full fidelity, it is so strongly correlated with ride quality and road loading that most research projects that have tested alternate statistics have not found significant improvements in correlation.

The IRI is measured using profilometers, which measure the road profile, or by correlating the measurements of RTRRMS to an IRI calculated from a profile.

Using World Bank terminology, these are respectively called Information Quality Level (IQL) 1 and IQL-3 devices, representing the relative accuracy of the measurements. A common misconception is that the 80 km/h used in the simulation must also be used when physically measuring roughness with an instrumented vehicle. IQL-1 systems measure the profile direction, independent of speed, and IQL-3 systems typically have correlation equations for different speeds to relate the actual measurements to IRI.

IQL-1 systems typically report the roughness at 10–20 m intervals; IQL-3 at 100m+ intervals. The data can be presented using a moving average to provide a “roughness profile”. These IRI profiles are sometimes used to evaluate new construction to determine bonus/penalty payments for contractors, and to identify specific locations where repairs or improvements (e.g., grinding) are recommended. The IRI is also a key determinant of vehicle operating costs which are used to determine the economic viability of road improvement projects.

4.4.2 Influence of IRI on the optical system of measurement

The first evaluation concerns the study of the influence of roughness on the optical system of measurement of TSD. To do this we have imposed a limit value of IRI gradually decreasing until the number of data is insufficient to evaluate a correlation with the FWD. Under study, the pavement presents a wide spectrum of values of IRI and lends itself well to this type of analysis which is shown in the following figures (4-3, 4-4, 4-5) for both carriageways.

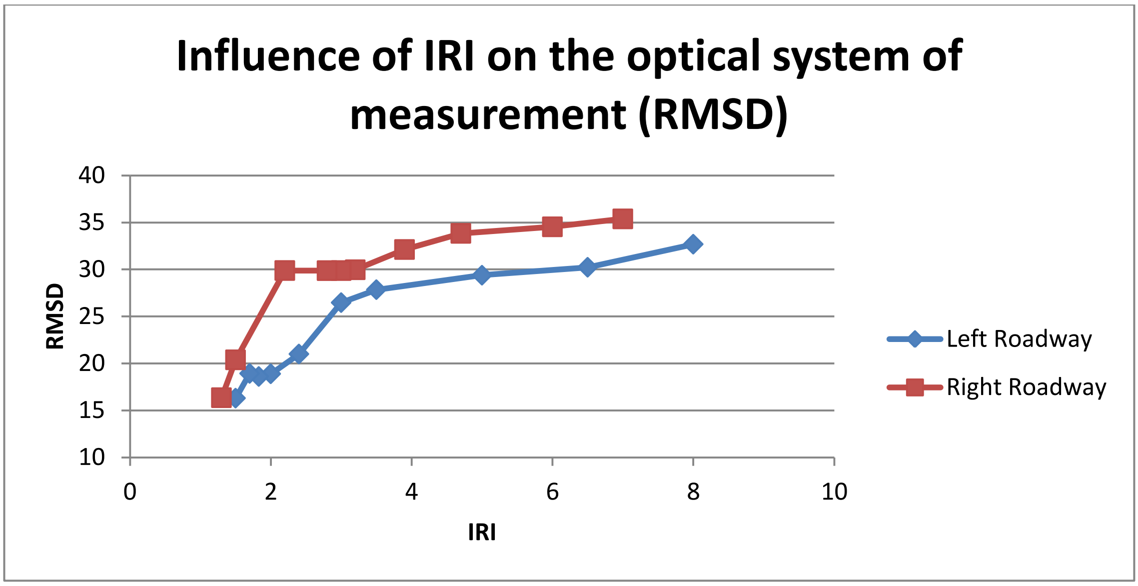

Figure 4 - 3 Influence of IRI on the optical system of measurement in terms of RMSD

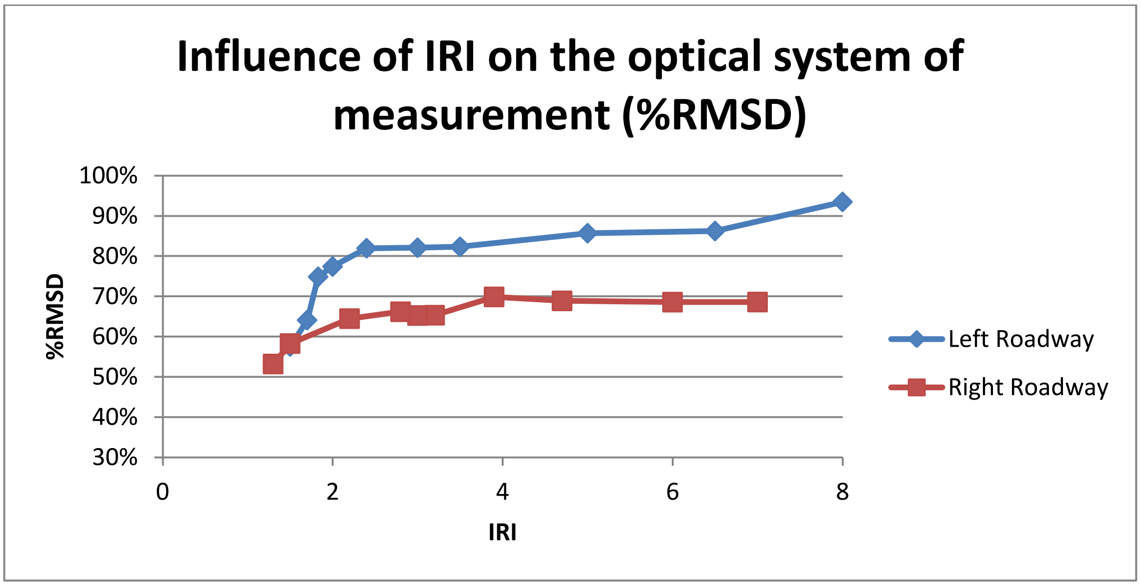

Figure 4 - 4 Influence of IRI on the optical system of measurement in terms of %RMSD

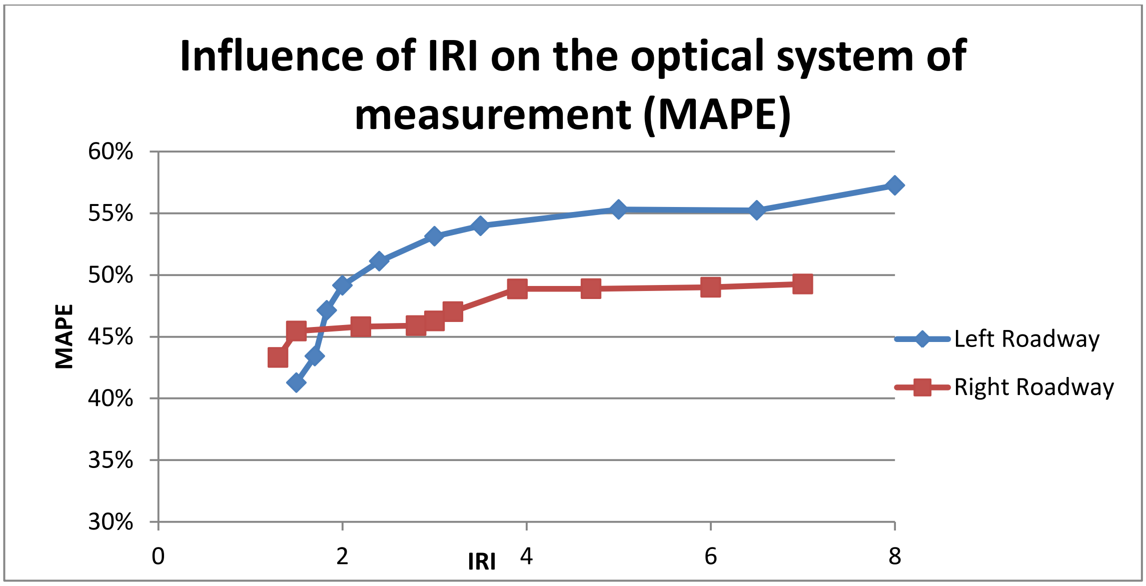

Figure 4 - 5 Influence of IRI on the optical system of measurement in terms of MAPE

From the graphs we can notice as reducing the value of IRI increases the degree of correlation between the two devices. In fact the dispersion of the data is reduced and the TDS's measurement can be associated with a reduced average error.

For example, taking only the data with the value of IRI lower than 1.5 we will get the following values of RMSD, %RMSD and MAPE for the two roadways (in parentheses is shown the values of the parameters without any constraint on IRI).

IRI<1.5	Left Roadway	Right Roadway
RMSD(µm)	16.23 (33.19)	20.38 (35.41)
%RMSD	57.24% (93.03%)	58.26% (68.59%)
MAPE	41.28% (57.08%)	45.46% (49.40%)

The statistical indexes show a marked improvement so an indication of a dependency between the roughness of the pavement and the optical measurement system of bearing capacity by Traffic Speed Deflectometer as we had supposed.
On average the dispersion indexes are reduced by 36% while the average error associated with the measurement of TSD is reduced by about 18%.

4.4.3 Influence of IRI on the increased dynamic load

To evaluate the influence of the increase of the dynamic load due to the irregularity of the surface, in addition to imposing limit values of IRI gradually decreasing, we deleted also those data that fell in a range of 20 m from the measurement that exceeded the fixed value of IRI. The results obtained will be compared with the previous case of imposition of a simple constraint on IRI in order to try to separate the effect of the irregularities on the dynamic load and on the optical system of measurement.

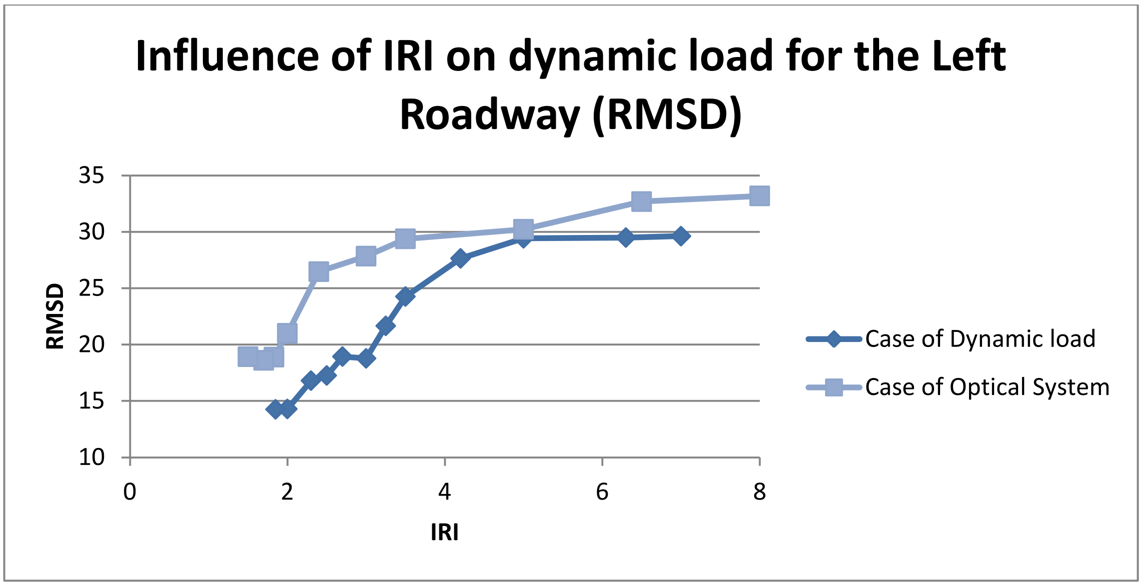

Figure 4 - 6 Influence of IRI on dynamic load for the left roadway in terms of RMSD

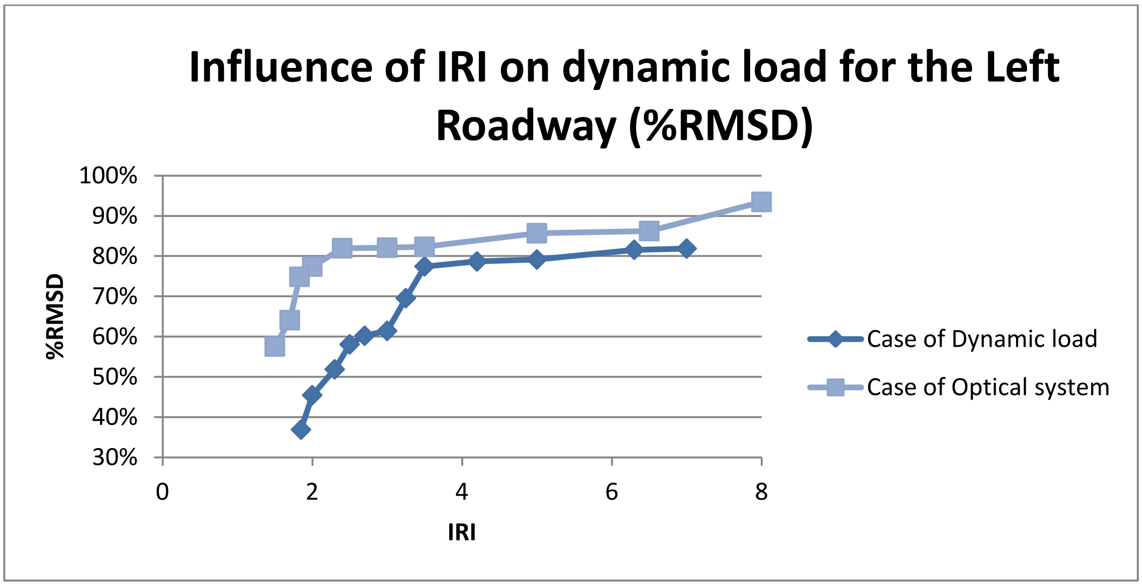

Figure 4 - 7 Influence of IRI on dynamic load for the left roadway in terms of %RMSD

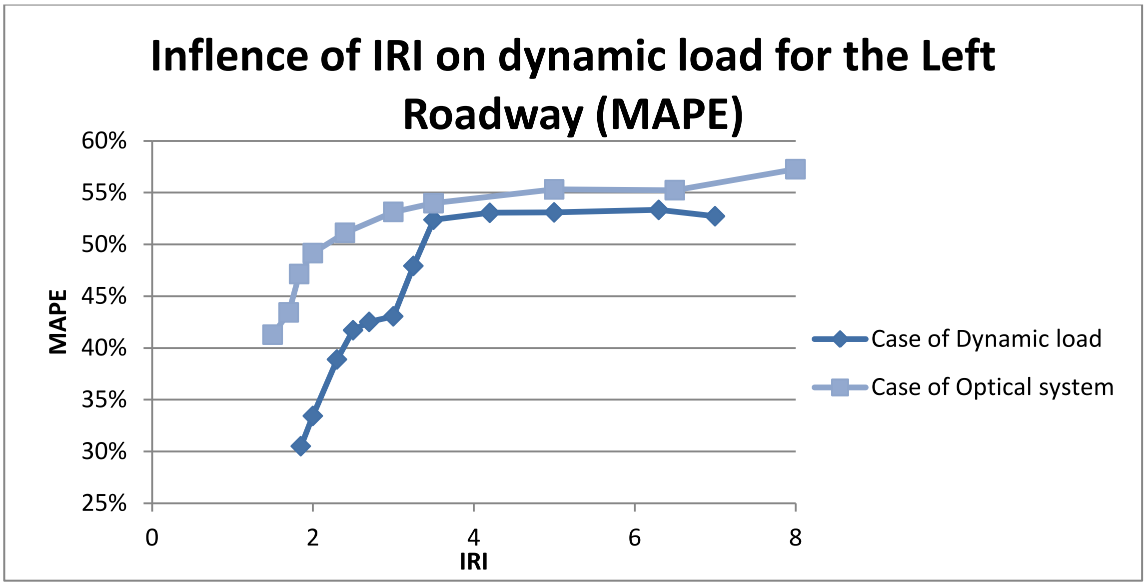

Figure 4 - 8 Influence of IRI on dynamic load for the left roadway in terms of MAPE

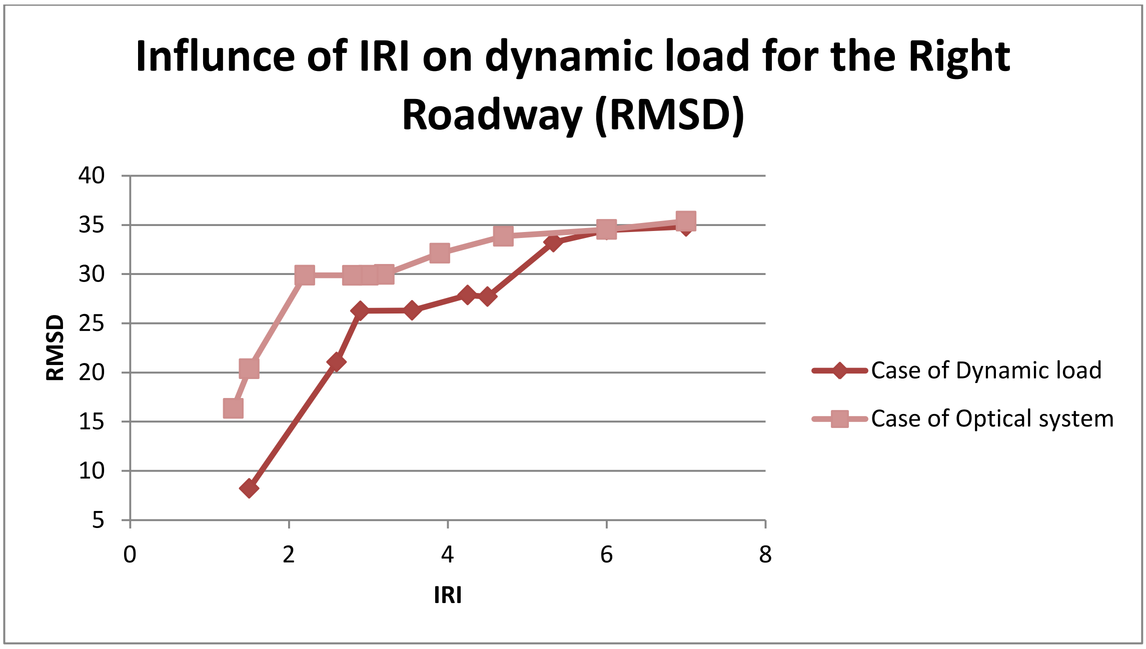

Figure 4 - 9 Influence of IRI on dynamic load for the right roadway in terms of RMSD

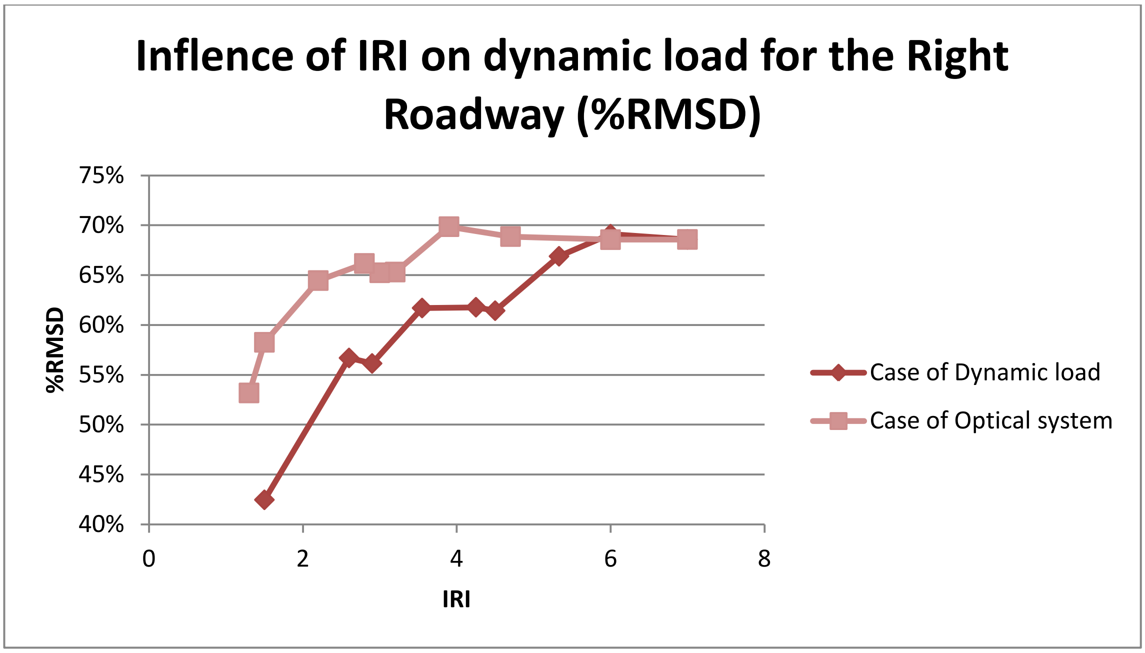

Figure 4 - 10 Influence of IRI on dynamic load for the right roadway in terms of %RMSD

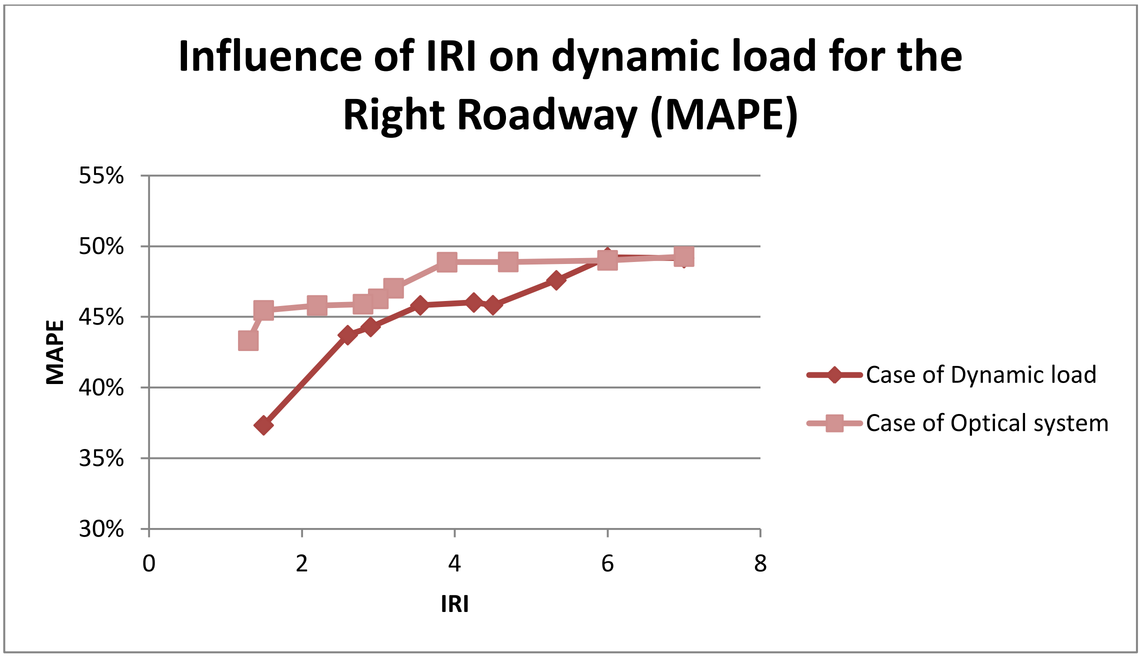

Figure 4 - 11 Influence of IRI on dynamic load for the right roadway in terms of MAPE

The results obtained by comparing with the previous case allow us to separate the effect that the roughness has on the variation of the dynamic load from the influence on the optical system. The imposition of this additional constraint has markedly improved the statistical indices and for IRI values <1.5 the results are reported in table.

IRI<1.5	Left Roadway	Right Roadway
RMSD(μm)	11.78 (16.23) ((33.19))	8.21 (20.38) ((35.41))
%RMSD	35.82% (57.24%) ((93.03%))	42.46% (58.26%) ((68.59%))
MAPE	28.5% (41.28%) ((57.08%))	37.33% (45.46%) ((49.40%))

Therefore we can conclude that the roughness of the surface also has a significant effect on the dynamic load of the Traffic Speed Deflectometer and so on the measurement of bearing capacity of the pavement.

To verify that the difference between the measurements by FWD and TSD did not depend in our case study from problems of the subgrade, we have examined whether there is a correlation between the errors in the measurement of SCI and the D900 (characteristic parameter of the condition of the subgrade) for the left and right carriageway.

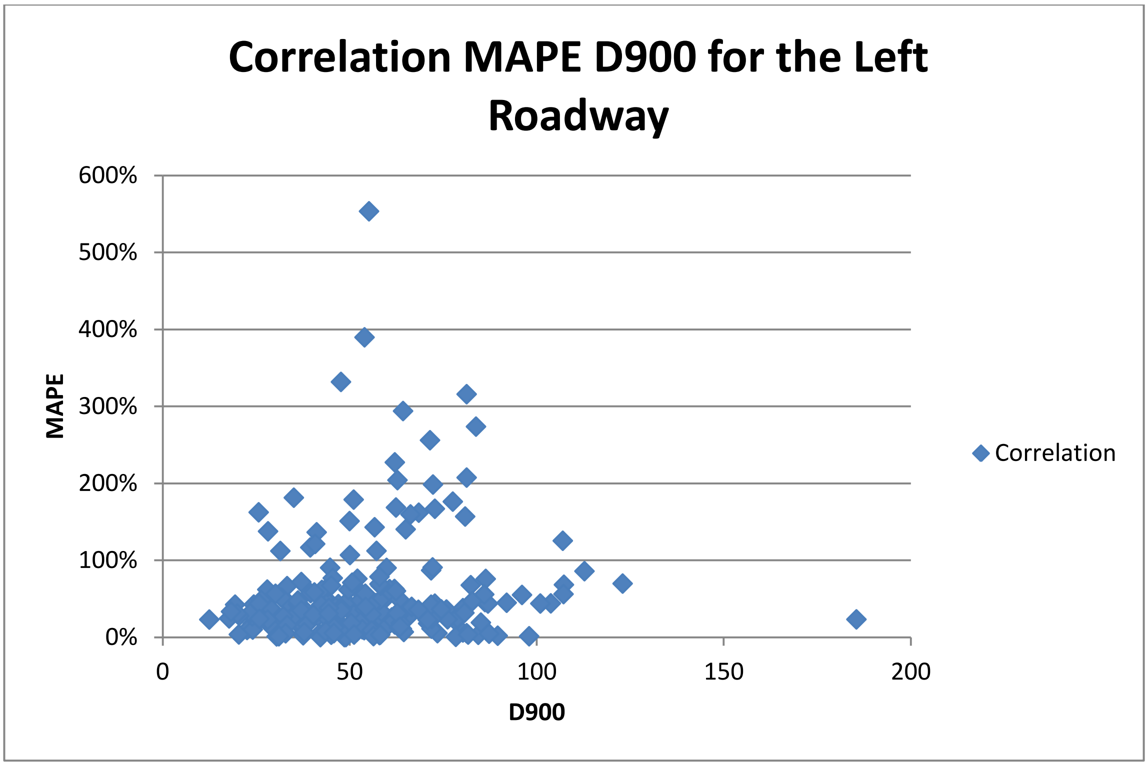

Figure 4 - 12 Correlation between MAPE and D900 for the Left Roadway

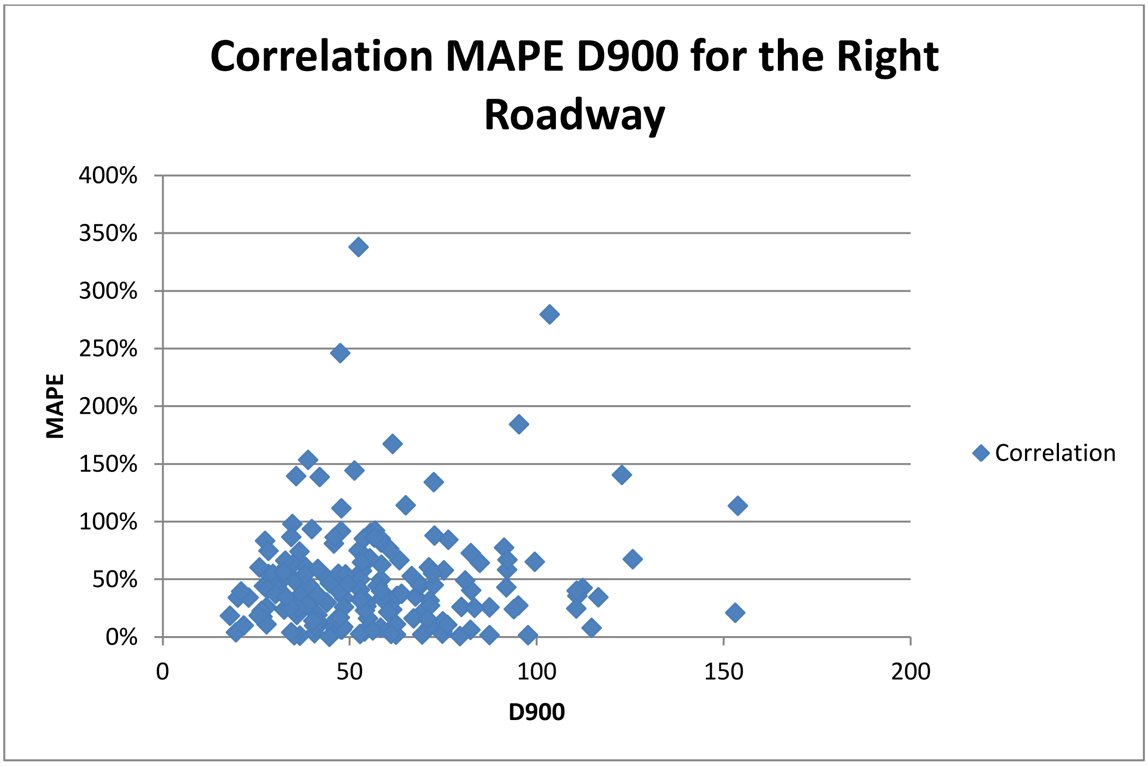

Figure 4 - 13 Correlation between MAPE and D900 for the Right Roadway

As is clear from the graphs we can’t find a correlation between the two parameters in fact the dispersion is homogeneous.

In conclusion we can state that the degree of roughness of the pavement affects greatly on the measures carried out by Traffic Speed Deflectometer (on the optical system of measurement and on the dynamic load applied), but by setting appropriate limitations on the value of IRI, the parameter which is provided by itself, its reliability against the FWD greatly improves with an average reduction of the indices of dispersion of 60% and a reduction of the mean error percentage associated to the measure of 38%.

4.5 Effects of temperature

Temperature is the main factor which affects the measurements of bearing capacity for the Traffic Speed Deflectometer and the Falling Weight Deflectometer as it is shown in the following tables comparing the corrected results with those uncorrected with the temperature.

Left Roadway	RMSD(µm)	%RMSD	MAPE
Uncorrected Data	45.14	135%	85%
Corrected Data	33.19	93.03%	57.08%

Right Roadway	RMSD(µm)	%RMSD	MAPE
Uncorrected Data	49.37	137.5%	97.85%
Corrected Data	35.41	68.59%	49.40%

The temperature correction formula proposed by ANAS, which standardizes the value of SCI300 at 14°C of air was calibrated at the National Road "Aurelia" SS1 at Km 23+500 as this road section is equipped with a constant monitoring system of temperature. The formula is:

$$\frac{SCI300_{14°C}}{SCI300_{T\ test}} = e^{(c\ \cdot(14-T_{test}))}$$

Where c = 0.037

To assess the degree of reliability of the formula in our case study we have adopt two correction curves with the temperature of air at the turn of ANAS's curve so adopting a value of c = 0036 and 0038 with the following results.

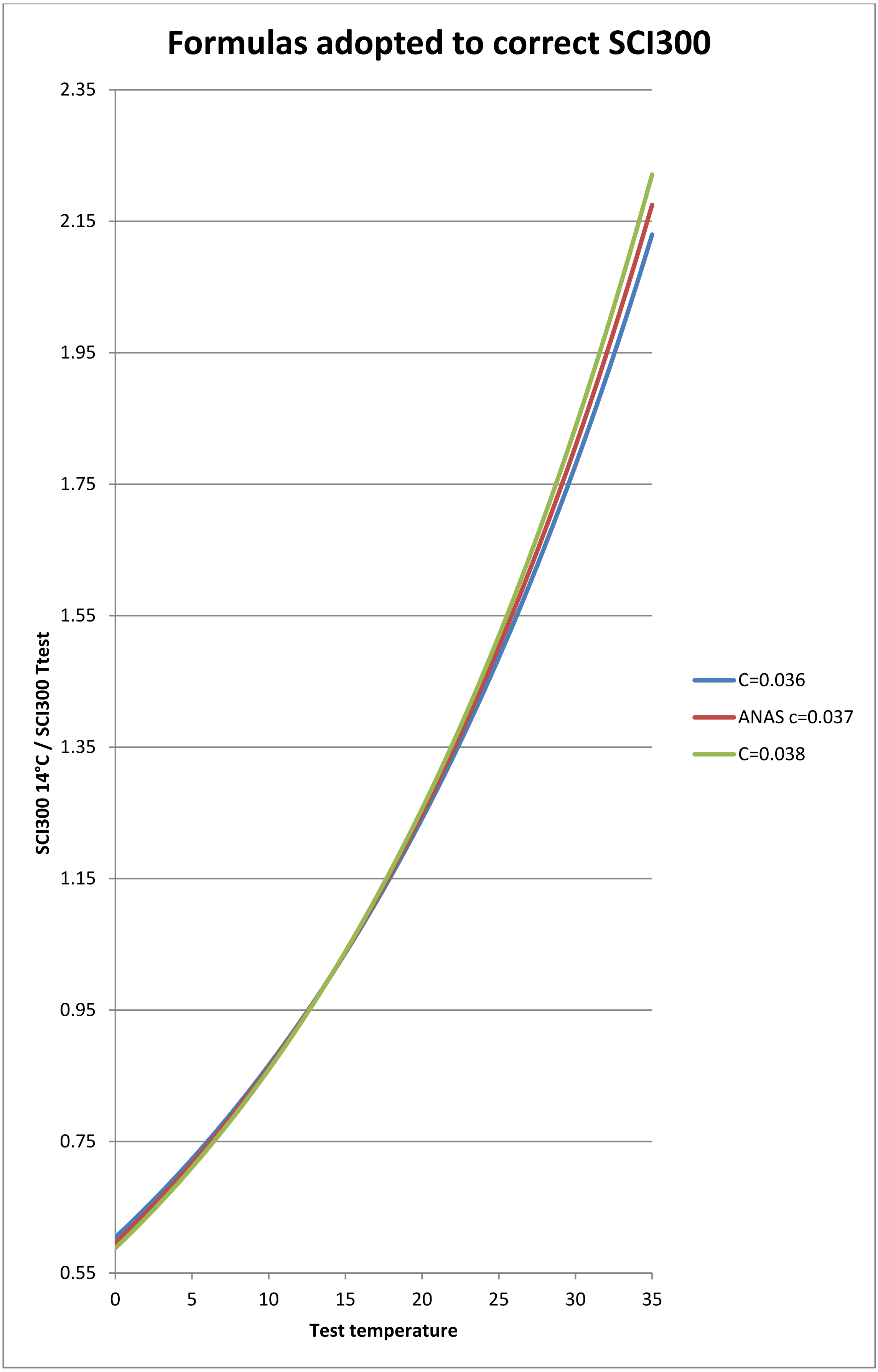

Figure 4 - 14 Formulas adopted to correct SCI300 with the temperature

c = 0.036	Left Roadway	Right Roadway
RMSD(μm)	34.55	35.32
%RMSD	94.44%	66.40%
MAPE	58.12%	48.63%

c = 0.037 ANAS	Left Roadway	Right Roadway
RMSD(μm)	33.19	35.41
%RMSD	93.03%	68.59%
MAPE	57.08%	49.40%

c = 0.038	Left Roadway	Right Roadway
RMSD(μm)	32.83	34.69
%RMSD	91.79%	64.27%
MAPE	56.26%	47.39%

From the results obtained we can state that using a curve for the correction of the bearing capacity with the temperature of air with constant c equal to 0.038 we obtain for both left and right roadway a better correlation between TSD and FWD respect to the calibrated formula from ANAS with c = 0.037 in our case study.

4.5.1 Temperature of pavement

In reviewing the literature on the topic of the temperature, it would seem more appropriate to correct the value of the bearing capacity of the pavement with the temperature of the pavement and not of the air because there isn't a direct relationship between them, but a relationship which depends on a series of factors such as: wind, radiation etc.. This could be the reason why in our case study adopting a factor c = 0.038, different from ANAS's factor, it yield the best results.

We try to create a relationship of correction of SCI300 with the temperature of the pavement and to do this we start from the following considerations extrapolate from the literature. According to the English specifications HD 29/08, "Design Manual for Road and Bridges – Data for Pavement Assessment", there is a relationship between the stiffness of the bituminous conglomerate and its temperature according to the relation:

$$E_{Ttest} = \frac{E_{20°C}}{10^{(0.0003\cdot(20-T_{test})-0.022\cdot(20-T_{test}))}}$$

Where:

Ttest = temperature of the asphalt at the time of testing (measured at 100mm depth)

E_{Ttest} = stiffness at temperature Ttest

$E_{20°C}$ = stiffness at 20°C

Meanwhile Collop, Armitage and Thom in 2001[19] found an almost linear relationship between the value of SCI and the stiffness of the asphalt layer, as reported in the Figure 4-15

19 Collop, A., Armitage, R., Thom, N., 2001. "Assessing variability of in situ pavement material stiffness moduli". Highway division, London, UK.

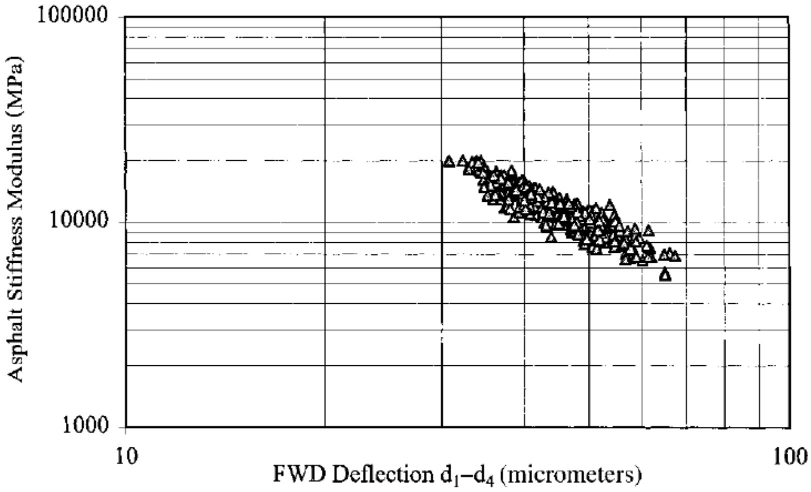

Figure 4 - 15 Relationship between Asphalt Stiffness and SCI300

With these assumptions it is possible to establish a relationship between the value of SCI300 and the temperature of the asphalt conglomerate, a coarse relationship whose parameters should be refined but if it gives good results, could be the basis for subsequent studies of calibration in order to confirm if not improve the correlation between the measurements by FWD and TSD. The formula is:

$$SCI300_{20°C} = \frac{SCI300_{Ttest}}{10^{(0.0003\cdot(20-T_{test})-0.022\cdot(20-T_{test}))}}$$

Where:

Ttest = temperature of the asphalt at the time of testing (measured at 100mm depth)

$SCI300_{Ttest}$ = the value of SCI300 at temperature Ttest

$SCI300_{20°C}$ = the value of SCI300 at 20°C

The formula of HD 29/08 needs knowledge of the temperature at depth of 100mm. This factor is missing but we get it by using the formula BELLS (3).

$$T_d = 0.95 + 0.892 \cdot IR + (\log(d) - 1.25) \cdot (-0.448 \cdot IR + 0.621 \cdot (1 - day) + 1.83 \cdot \sin(hr_{18} - 15.5)) + 0.042 \cdot IR \cdot \sin(hr_{18} - 13.5)$$

Where:

T_d = Pavement temperature at depth d, °C

IR = Pavement surface temperature, °C

log = Base 10 logarithm

d = Depth at which mat temperature is to be predicted, mm

1-day = Average air temperature the day before testing, °C

sin = Sine function on an 18-hr clock system, with 2π radians equal to one 18-hr cycle

hr_{18} = Time of day, in a 24-hr clock system, but calculated using an 18-hr asphalt concrete (AC) temperature rise-and-fall time cycle, as indicated in Figure 4-16

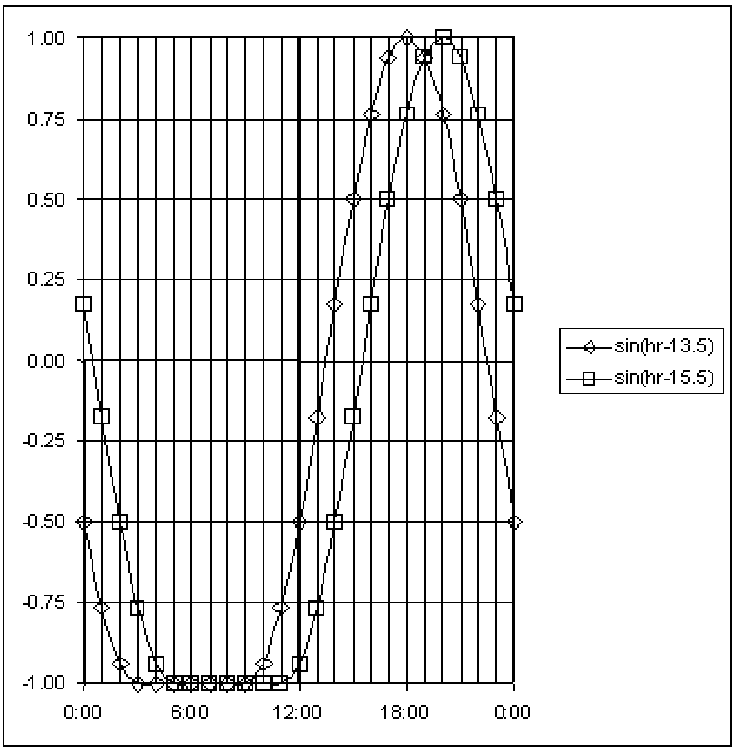

Figure 4 - 16 18-hr Sine function used in BELLS equations

The results are shown in the following table and are compared with those of the formula of ANAS in parentheses.

	Left Roadway	Right Roadway
RMSD(μm)	31.42 (33.19)	34.59 (35.41)
%RMSD	62.89% (93.03%)	61.35% (68.59%)
MAPE	46.71% (57.98%)	34.59% (49.40%)

There is a clear improvement of statistical indices with an average reduction of the error associate with the measurement of 26%. It would recommend a better calibration of the formula with additional data that ANAS could easily find from its temperature monitoring station at the Aurelia National road .

In this last phase of the study we have used this formula, imposing a value of IRI less than 1.5, to assess the benefit reached.

IRI<1.5	Left Roadway	Right Roadway
RMSD(μm)	6.74 (33.19)	13.47 (35.41)
%RMSD	24.53% (93.03%)	27.73% (68.59%)
MAPE	20.93% (57.98%)	21.30% (49.40%)

What we get is a clear improvement over the results obtained by ANAS showing a better correlation between the TSD and FWD under certain constraints. The indices of dispersion have been reduced on average by 70% while the average error rate associated with the measurement has been reduced by 51%, amounting to the value of about 21% which is very good for a use at network level.

4.6 Conclusion

The reliability of the Traffic Speed Deflectometer at network level has been verified statistically and by imposing restrictions on the IRI value the correlation between TSD and FWD is strengthened.

By analyzing the influence of temperature we have obtained that if we refer the temperature of the pavement rather than of air, the measurements of bearing capacity by Traffic Speed Deflectometer will be more reliable.

Future studies should be directed to a better calibration of the dependency relationship between SCI300 and the temperature of the pavement as it seems to give better results in terms of correlation between TSD and FWD. The purpose is to facilitate the acceptance of the TSD as a new tool for the verification and acceptance of the work.

CONCLUSION

The importance of performing measurements of bearing capacity by Traffic Speed Deflectometer is in the opportunity to acquire data continuously and at high speed. These features make it an ideal tool for the various National Agencies that have to manage large road networks in terms of acceptance of the work and implementation of maintenance programs. A high-efficiency device, as the TSD, allows to acquire the value of the bearing capacity in a quick low-cost way and without interrupting the circulation.

From the studies undertaken, the irregularities of the road surface affect the TSD optical measurement system and the dynamic load applied to the pavement, but are only qualitative assessments. In addition, National Agencies evaluate the influence of temperature on the bearing capacity in a different way, providing for its control different valuation techniques.

The data set provided by ANAS, acquired with Traffic Speed Deflectometer and Falling Weight Deflectometer, gives a standard deviation and a percentage standard deviation (% RMSD and RMSD) between the two devices equal to 34.1 μm and 80.5% so there is a certain dispersion of the data, while the average percentage error (MAPE) is about 53%.

To assess the influence of the irregularity of the pavement on the optical measurement system, we imposed decreasing limit values of IRI showing an improvement of the correlation between TSD and FWD. When IRI is less than 1.5, the statistical dispersion indices are reduced by 36%, while the average percentage error (MAPE) associated with the measurement is decreased by 18% dropping to 43%.

A further improvement is obtained by considering the effect that the irregularity has on the dynamic load applied to the pavement so, in addition to imposing gradually decreasing limit values of IRI, we have deleted those data that fell in a range of 20 m from the measurements that exceeded the value of the parameter set. In the case of IRI less than 1.5, dispersion indexes are reduced by 60% compared to the first case, while the average percentage error (MAPE) has improved by 38% reaching a value of 32.8%.

The temperature is the most influencing parameter on the measure of bearing capacity in fact without making a correction of the structural indices (SCI300), we would get a standard deviation and a percentage standard deviation (% RMSD and RMSD) respectively 47 μm and 136%, while the average percentage error (MAPE) on the measure would rise to 92%. These values of the statistical indices would give a total lack of correlation between the two devices while using the ANAS's correction formula calibrated with the temperature of the air, we obtain a clear improvement of the reliability of the TSD.

As a starting point for future studies, we determined a relationship between the structural index (SCI300) and the temperature of the bituminous conglomerate, based on researches that consider this parameter like those that mainly affects the stiffness of the material and so on the overall bearing characteristics of the pavement. This formulation has been tested on the set of data available, allowing to achieve a clear improvement of all statistical indexes. In particular, setting a value of IRI less than 1.5, we obtain a reduction of the dispersion indices (RMSD and RMSD%) by 70%, while the average percentage error (MAPE) associated to measure a decrease of 51% to reach a value equal to 21%.

In conclusion, the results mentioned above allow to emphasize the influence of surface irregularities on the reliability of the correlation between TSD and FWD. Regarding the temperature of the pavement, the preliminary processing carried out in this work, highlight its fundamental importance in the correct evaluation of the bearing capacity of the asphalt layers. In particular, the use of the assumed relationship allows, as in the case of IRI, to increase the correlation coefficient between the two devices.

Lastly, we believe further studies in this topic should be directed to the verification of the assumptions we used in the present work, providing, where appropriate, validation based on a larger sample data, which takes into account different hierarchical infrastructures.

CONCLUSIONE

L'importanza di eseguire misure di portanza mediante Traffic Speed Deflectometer risiede nella possibilità di acquisire i dati in continuo e ad alta velocità. Queste caratteristiche lo rendono uno strumento ideale per le varie Agenzie Nazionali che si trovano a dover gestire vaste reti stradali in termini di accettazione dei lavori e attuazione di programmi di manutenzione. Uno strumento ad alto rendimento, come il TSD, permette quindi di acquisire il valore della portanza in modo rapido, a basso costo operativo e senza intralciare la circolazione.

Dagli studi effettuati sino ad oggi emerge che le irregolarità della superficie stradale influiscono sia sul sistema ottico di misura del TSD che sul carico dinamico applicato alla pavimentazione, pur rimanendo valutazioni di natura qualitativa. Inoltre, le singole Agenzie Nazionali valutano l'influenza della temperatura sulla portanza in modo diverso, prevedendone il controllo attraverso tecniche di valutazione distinte.

Il set di dati fornito da ANAS, acquisito con Traffic Speed Deflectometer e Falling Weight Deflectometer, ha dato una standard deviation e una standard deviation percentuale (RMSD e %RMSD) tra i due strumenti pari a 34.1 μm e 80.5% quindi si riscontra una certa dispersione del dato, mentre l'errore medio percentuale (MAPE) è di circa il 53%.

Per valutare l'influenza delle irregolarità della pavimentazione sul sistema ottico di misura si è imposto dei valori limite decrescenti di IRI riuscendo così a evidenziare un miglioramento della correlazione tra TSD e FWD. Per IRI minori di 1.5 gli indici statistici di dispersione si sono ridotti del 36%, mentre l'errore medio percentuale (MAPE) associato alla misura è diminuito del 18% portandosi al 43%.

Un ulteriore miglioramento si è ottenuto considerando l'effetto che l'irregolarità ha sul carico dinamico applicato alla pavimentazione quindi, oltre ad imporre valori limite di IRI via via decrescenti, si sono eliminati anche quei dati che ricadevano in un intervallo di 20 m dalla misura che eccedeva il valore del parametro fissato. Nel caso di IRI minore di 1.5 gli indici di dispersione si sono ridotti del 60% rispetto al caso iniziale, mentre l'errore medio percentuale (MAPE) ha registrato un miglioramento del 38% portandosi ad un valore del 32.8%.

La temperatura rimane il parametro che influenza maggiormente la misura di portanza infatti non apportando una correzione agli indici strutturali, si otterrebbe una standard devation e una standard deviation percentuale (RMSD e %RMSD) pari rispettivamente a 47 μm e 136%, mentre l'errore medio percentuale (MAPE) sulla misura sarebbe salito al 92%. Questi valori degli indici statistici darebbero una assoluta assenza di correlazione tra i due strumenti mentre, utilizzando la formula di correzione della portanza calibrata da ANAS con la temperatura dell'aria, si perviene ad un netto miglioramento dell'affidabilità del TSD. Come punto di inizio per studi futuri si è voluto determinare una relazione tra l'indice strutturale e la temperatura del conglomerato bituminoso, basandoci su ricerche che vedono proprio in quest'ultimo parametro quello che maggiormente incide sulla rigidezza dei materiali e quindi sulle caratteristiche portanti complessive della pavimentazione. Tale formulazione è stata testata sul set di dati a diposizione consentendo di raggiungere un netto miglioramento di tutti gli indici statistici. In particolare fissando un valore di IRI minore di 1.5 otteniamo una riduzione degli indici di dispersione (RMSD e %RMSD) del 70%, mentre per l'errore medio percentuale (MAPE) associato alla misura una diminuzione del 51% portandosi ad un valore pari al 21%.

In conclusione, i risultati precedentemente richiamati permettono di sottolineare l'influenza delle irregolarità superficiali sull'affidabilità della correlazione tra TSD e FWD. Per quanto attiene la temperatura della pavimentazione, le elaborazioni preliminari condotte nell'ambito del presente lavoro ne evidenziano la fondamentale importanza ai fine della corretta valutazione della capacità portante degli strati bituminosi della pavimentazione. In particolare, l'utilizzo della relazione ipotizzata permette, come nel caso dell'IRI, di incrementare il coefficiente di correlazione tra i due strumenti.

Si ritiene infine che i successivi studi al riguardo debbano essere rivolti alla verifica delle ipotesi assunte nel presente lavoro di tesi, prevedendone, eventualmente, la validazione sulla base di un più ampio campione di dati, che prenda in considerazione infrastrutture di ambito gerarchico diverso.

APPENDIX A

To manage the amount of data which ANAS provided us, it was necessary to create a program in PHP. The software is able to perform the correlations between the measurements acquired with Traffic Speed Deflectometer and Falling Weight Deflectometer setting some parameters and plotting solutions.

Below is the code of the program.

```
<html><title>Calcolo Carico Dinamico - Tommaso Paoletti
Lorenzetti</title><body>
<?
if (!$_GET['modo']) {

echo "<h4>Calcolo Grezzo</h4>";
echo "<input type='button'
onClick=document.location='index.php?modo=1&carr=sinistra' '
value='Avvia (carr. sinistra)'>";
echo "   ";
echo "<input type='button'
onClick=document.location='index.php?modo=1&carr=destra' '
value='Avvia (carr. destra)'>";

echo "<br><br><br><br><h4>Calcolo IRI</h4>";
echo "IRI <input type='text' size='4' id='iri1' value=''> ";
echo "<input type='button'
onClick=document.location='index.php?modo=2&iri='+document.getElementB
yId('iri1').value+'&carr=sinistra'; value='Avvia (carr. sinistra)'>";
echo "   ";
echo "<input type='button'
onClick=document.location='index.php?modo=2&iri='+document.getElementB
yId('iri1').value+'&carr=destra'; value='Avvia (carr. destra)'>";

echo "<br><br><br><br><h4>Calcolo Carico Dinamico</h4>";
echo "IRI <input type='text' size='4' id='iri2' value=''> ";
echo "<input type='button'
onClick=document.location='index.php?modo=3&iri='+document.getElementB
yId('iri2').value+'&carr=sinistra'; value='Avvia (carr. sinistra)'>";
echo "   ";
echo "<input type='button'
onClick=document.location='index.php?modo=3&iri='+document.getElementB
yId('iri2').value+'&carr=destra'; value='Avvia (carr. destra)'>";


} else {
$carr = $_GET['carr'];
$modo = (int) $_GET['modo'];
if ($modo > 1) $iri = (float) $_GET['iri'];
```

```
$fwd = array();
$tsd = array();

if ($carr == 'sinistra') $fwd_filename = "./FWDleft.csv";
else if ($carr == 'destra') $fwd_filename = "./FWDright.csv";

if (($fwd_file = fopen($fwd_filename, "r")) !== FALSE) {

while (($data = fgetcsv($fwd_file, 100, ";")) !== FALSE) {
$pos = $data[0];
$pos = str_replace(",", ".", $data[0]);
if (strlen($pos) < 6) $pos .= 0;
if (substr((string) $data[1], 0, 1) != '-') $fwd[$pos] =
str_replace(",", ".", $data[1]);
}
//print_r($fwd); exit;
}

if ($carr == 'sinistra') $tsd_filename = "./TSDleft.csv";
else if ($carr == 'destra') $tsd_filename = "./TSDright.csv";

if (($tsd_file = fopen($tsd_filename, "r")) !== FALSE) {

while (($data = fgetcsv($tsd_file, 100, ";")) !== FALSE) {
$pos = $data[0];
$pos = str_replace(",", ".", $data[0]);
if (strlen($pos) < 6) $pos .= 0;

if ((substr((string) $data[2], 0, 1) != '-') && ($data[2] !=
"#VALUE!"))
$tsd[$pos] = array(str_replace(",", ".", $data[1]), str_replace(",",
".", $data[2]));

}

}

fclose($tsd_file);
fclose($fwd_file);



$scarto_tot = 0;
$scarto_perc_tot = 0;
$dettaglio = "<h3>Elenco valori</h3>";
$tabella = "<center><table border='1' cellpadding='5'><tr style='font-
weight:bold'><td>DISTANZA</td><td>FWD</td><td>TSD</td><td>IRI</td><td>
SQM</td><td>SQM%</td></tr>";
$num_valori = 0;

foreach($fwd AS $fwd_dist => $fwd_val) {

$fwd_dist_2prec = (float) ($fwd_dist - 0.02);
$fwd_dist_prec = (float) ($fwd_dist - 0.01);
$fwd_dist_succ = (float) ($fwd_dist + 0.01);
$fwd_dist_2succ = (float) ($fwd_dist + 0.02);


if (array_key_exists($fwd_dist, $tsd)) {
if (
($modo == 1) ||
```

```
( ($modo == 2) && ($tsd[$fwd_dist][0] < $iri) ) ||
( ($modo == 3) && ($tsd[$fwd_dist][0] < $iri) &&
((array_key_exists("$fwd_dist_2prec", $tsd) &&
($tsd["$fwd_dist_2prec"][0] < $iri)) ||
(!array_key_exists("$fwd_dist_2prec", $tsd)))
&&
((array_key_exists("$fwd_dist_prec", $tsd) &&
($tsd["$fwd_dist_prec"][0] < $iri)) ||
(!array_key_exists("$fwd_dist_prec", $tsd) ))
&&
((array_key_exists("$fwd_dist_succ", $tsd) &&
($tsd["$fwd_dist_succ"][0] < $iri)) ||
(!array_key_exists("$fwd_dist_succ", $tsd) ))
&&
((array_key_exists("$fwd_dist_2succ", $tsd) &&
($tsd["$fwd_dist_2succ"][0] < $iri)) ||
(!array_key_exists("$fwd_dist_2succ", $tsd) ))
)
) {
$num_valori++;
$scarto = pow($tsd[$fwd_dist][1] - $fwd_val, 2);
$scarto_perc = pow($tsd[$fwd_dist][1] - $fwd_val, 2) / pow($fwd_val,
2);
$scarto_tot += $scarto;
$scarto_perc_tot += $scarto_perc;

$dettaglio .= "Distanza: " . $fwd_dist. "<br>";
$dettaglio .= "FWD: " . $fwd_val . "<br>";
$dettaglio .= "TSD: ". $tsd[$fwd_dist][1] . "<br>";
$dettaglio .= "IRI: " . $tsd[$fwd_dist][0] . "<br>";
$dettaglio .= "<b>Scarto quadratico: " . number_format($scarto, 6) .
"</b><br><br>";

$tabella .= "<tr><td>" . $fwd_dist . "</td><td>" . $fwd_val .
"</td><td>" . $tsd[$fwd_dist][1] . "</td><td>" . $tsd[$fwd_dist][0] .
"</td>";
$tabella .= "<td>" . number_format($scarto, 6, ".", "") . "</td><td>"
. number_format($scarto_perc, 6, ".", "") . "</td></tr>";
}
}
}

$tabella .= "</table></center>";

echo "<br><center><h3>CARREGGIATA " . strtoupper($carr) .
"</h3><h3>SCARTO QUADRATICO MEDIO: " . sqrt($scarto_tot/$num_valori) .
"</h3>";
echo "<h3>SCARTO QUADRATICO MEDIO PERCENTUALE: " .
sqrt($scarto_perc_tot/$num_valori) . "</h3>";
echo "<h3>NUMERO VALORI: " . $num_valori . " (" .
number_format(($num_valori / count($fwd)) * 100, 2) .
"%)</h3></center>";

echo $tabella;

echo "<br><center><iframe width='1200' height='400'
src='plot.php?modo=" . $modo . "&iri=" . $iri . "&carr=" . $carr . "'
frameborder='0'></center>";
```

```
echo "<!-- ";
echo "<pre>";
echo "************************************<br>";
echo " TSD <br>";
echo "************************************<br><br>";
print_r($tsd);
echo "<br><br><br>";
echo "************************************<br>";
echo " FWD <br>";
echo "************************************<br><br>";
print_r($fwd);
echo "</pre>";
echo " -->";

}

?>
</body>
</html>

<?php
//Include the code
require_once 'phplot.php';

$modo = (int) $_GET['modo'];
if ($modo > 1) $iri = (float) $_GET['iri'];
$carr = $_GET['carr'];

$fwd = array();
$tsd = array();

if ($carr == 'sinistra') $fwd_filename = "./FWDleft.csv";
else if ($carr == 'destra') $fwd_filename = "./FWDright.csv";

if (($fwd_file = fopen($fwd_filename, "r")) !== FALSE) {

while (($data = fgetcsv($fwd_file, 100, ";")) !== FALSE) {
$pos = $data[0];
$pos = str_replace(",", ".", $data[0]);
if (strlen($pos) < 6) $pos .= 0;

if (substr((string) $data[1], 0, 1) != '-') $fwd[$pos] =
str_replace(",", ".", $data[1]);

}

}

if ($carr == 'sinistra') $tsd_filename = "./TSDleft.csv";
else if ($carr == 'destra') $tsd_filename = "./TSDright.csv";

if (($tsd_file = fopen($tsd_filename, "r")) !== FALSE) {

while (($data = fgetcsv($tsd_file, 100, ";")) !== FALSE) {
$pos = $data[0];
$pos = str_replace(",", ".", $data[0]);
if (strlen($pos) < 6) $pos .= 0;

if ((substr((string) $data[2], 0, 1) != '-') && ($data[2] !=
```

```
"#VALUE!"))
$tsd[$pos] = array(str_replace(",", ".", $data[1]), str_replace(",",
".", $data[2]));

}

}

fclose($tsd_file);
fclose($fwd_file);

$example_data = array();

$scarto_tot = 0;
$dettaglio = "<h3>Elenco valori</h3>";
$num_valori = 0;

foreach($fwd AS $fwd_dist => $fwd_val) {

$fwd_dist_2prec = (float) ($fwd_dist - 0.02);
$fwd_dist_prec = (float) ($fwd_dist - 0.01);
$fwd_dist_succ = (float) ($fwd_dist + 0.01);
$fwd_dist_2succ = (float) ($fwd_dist + 0.02);


if (array_key_exists($fwd_dist, $tsd)) {
if (
($modo == 1) ||
( ($modo == 2) && ($tsd[$fwd_dist][0] < $iri) ) ||
( ($modo == 3) && ($tsd[$fwd_dist][0] < $iri) &&
((array_key_exists("$fwd_dist_2prec", $tsd) &&
($tsd["$fwd_dist_2prec"][0] < $iri)) ||
(!array_key_exists("$fwd_dist_2prec", $tsd)))
&&
((array_key_exists("$fwd_dist_prec", $tsd) &&
($tsd["$fwd_dist_prec"][0] < $iri)) ||
(!array_key_exists("$fwd_dist_prec", $tsd) ))
&&
((array_key_exists("$fwd_dist_succ", $tsd) &&
($tsd["$fwd_dist_succ"][0] < $iri)) ||
(!array_key_exists("$fwd_dist_succ", $tsd) ))
&&
((array_key_exists("$fwd_dist_2succ", $tsd) &&
($tsd["$fwd_dist_2succ"][0] < $iri)) ||
(!array_key_exists("$fwd_dist_2succ", $tsd) ))
)
) {
$num_valori++;
$scarto = pow($tsd[$fwd_dist][1] - $fwd_val, 2);
$scarto_tot += $scarto;
$tsd_val = $tsd[$fwd_dist][1];
$iri_val = $tsd[$fwd_dist][0];

$dettaglio .= "Distanza: " . $fwd_dist. "<br>";
$dettaglio .= "FWD: " . $fwd_val . "<br>";
$dettaglio .= "TSD: ". $tsd_val . "<br>";
$dettaglio .= "IRI: " . $iri_val . "<br>";
$dettaglio .= "<b>Scarto quadratico: " . number_format($scarto, 6) .
"</b><br><br>";

$example_data[] = array((float) $fwd_dist, $fwd_val, $tsd_val);
```

```
}
}
}

$example_data = array_reverse($example_data);
//Define the object
$plot = new PHPlot(1200, 400);


$plot->SetDataValues($example_data);

//Turn off X axis ticks and labels because they get in the way:
//$plot->SetXTickLabelPos('none');
//$plot->SetXTickPos('plotdown');
//$plot->SetXTickIncrement(1);
$plot->SetXTickPos('none');

$i = 1;
function campiona_x($value)
{
global $i;
$i++;
if ($i % 10 == 0) return $value;
else return "";
}
$plot->SetXLabelType('custom', 'campiona_x');

# Make a legend for the 2 functions:
$plot->SetLegend(array('FWD', 'TSD'));
$plot->SetDataColors(array('red', 'blue'));

//Draw it
$plot->DrawGraph();
?>
```

TABLE OF FIGURES

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Chapter 4

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